Hubble-Delayed Vacuum Decay

and Its Gravitational Wave Signals

Haipeng An (Tsinghua University)

ICTS Colloquium, Sep 11, 2026

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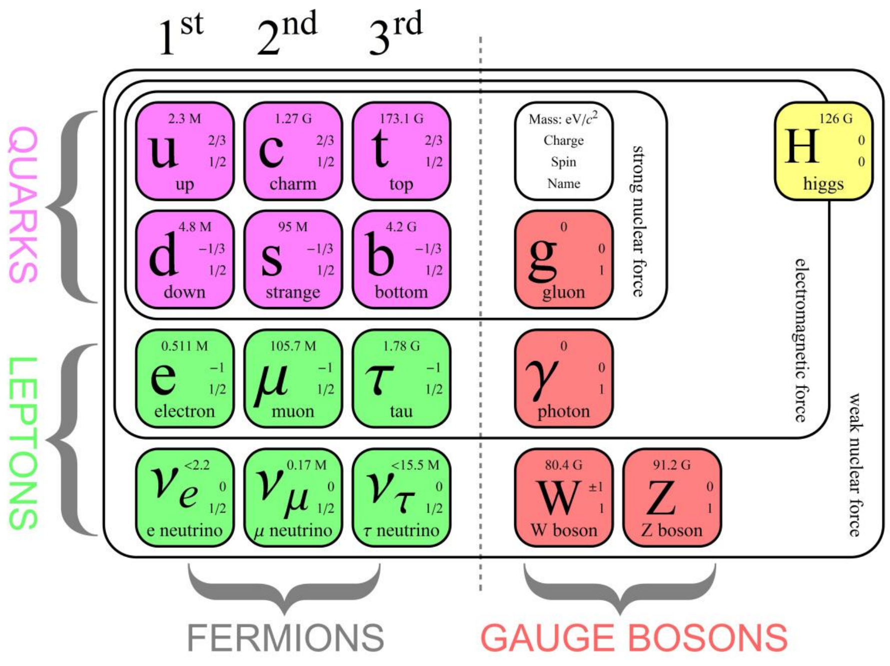
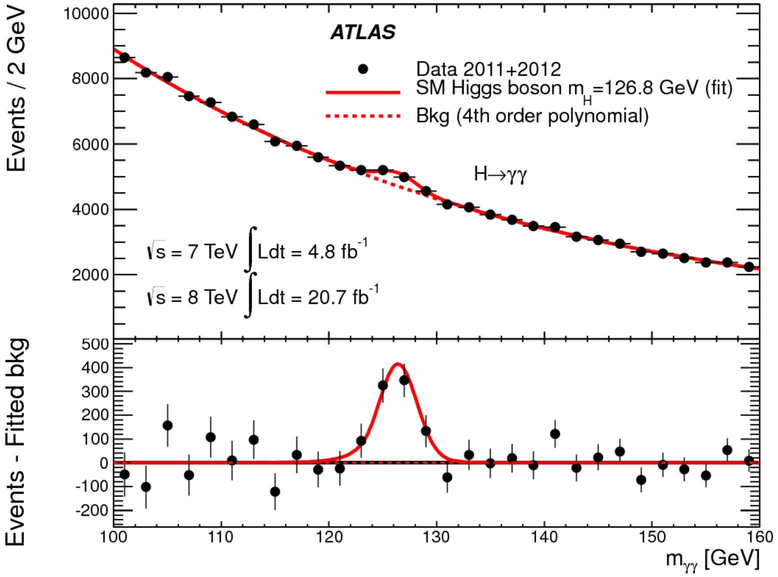
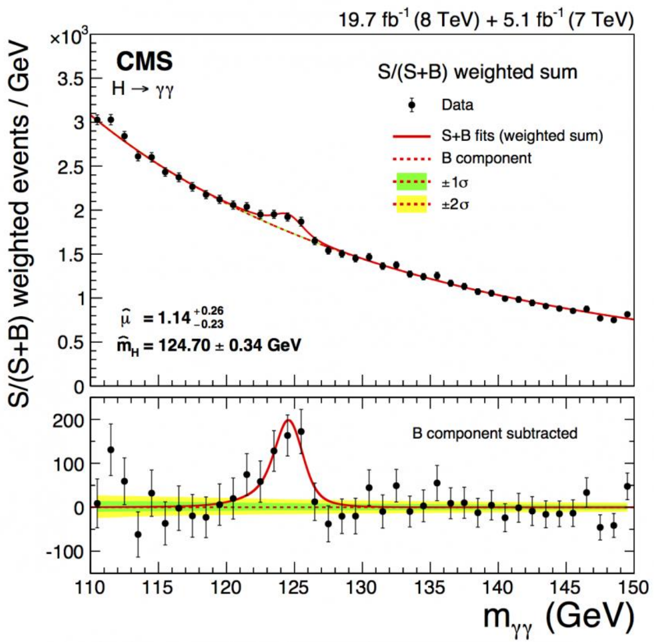
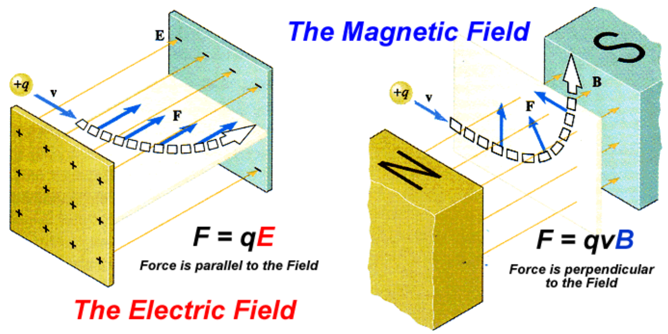
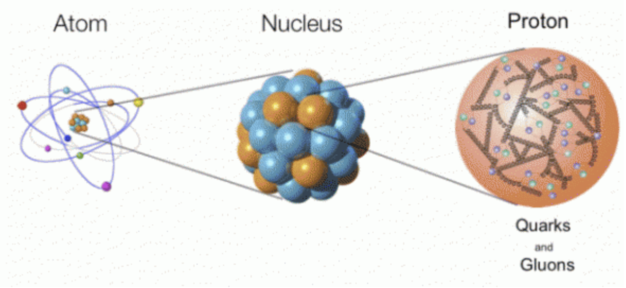
Our understanding of particle physics

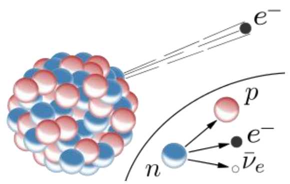




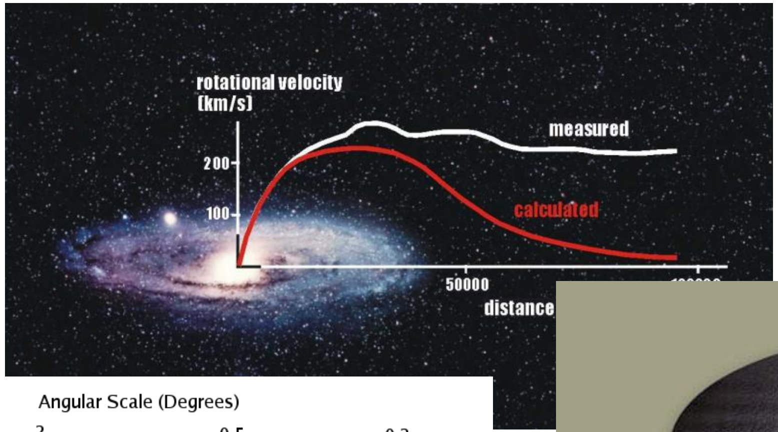


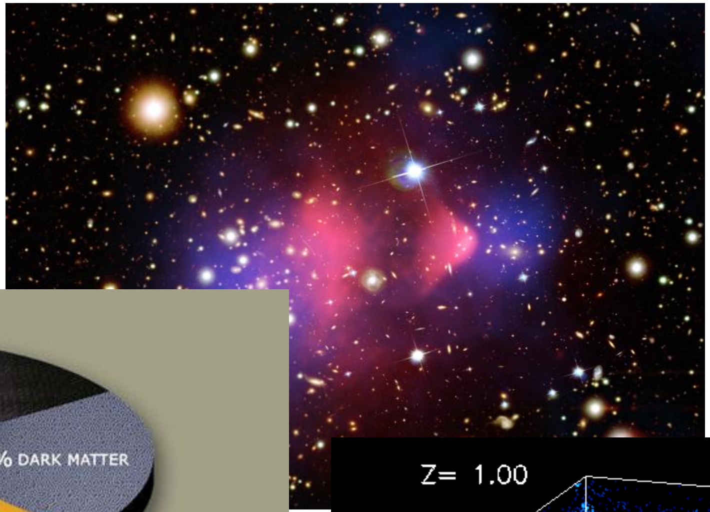


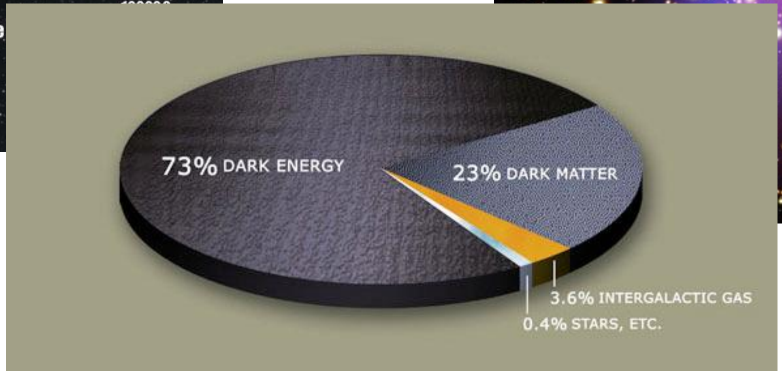


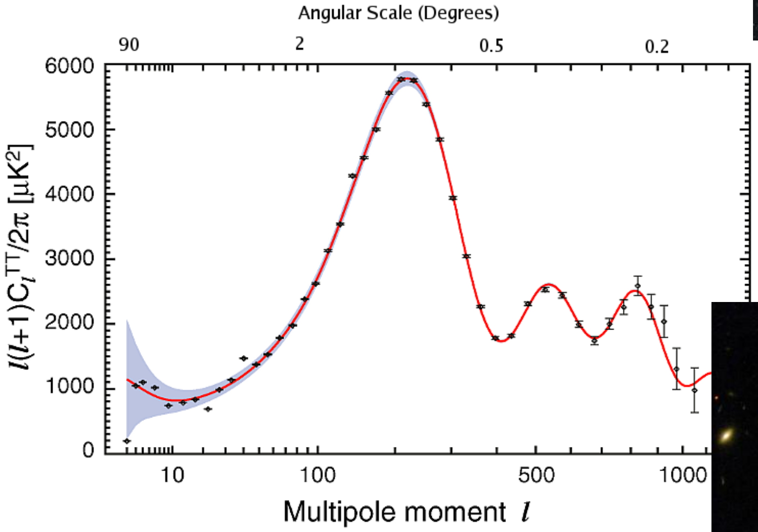


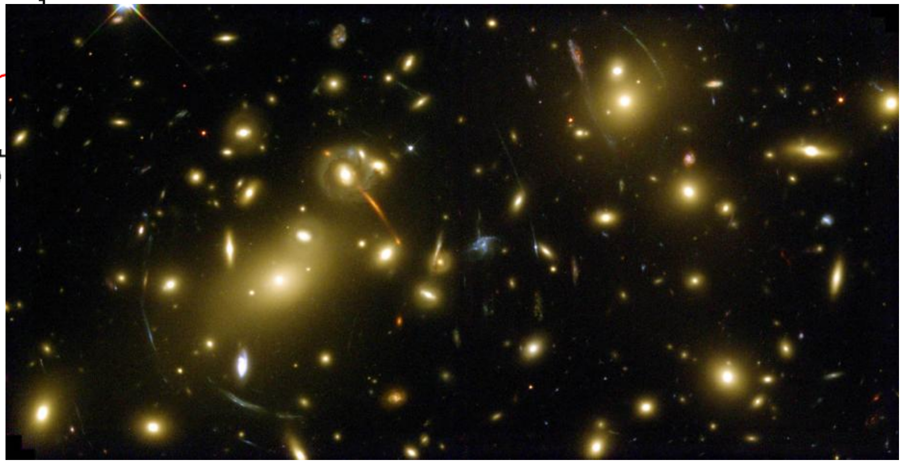
Our understanding of the universe

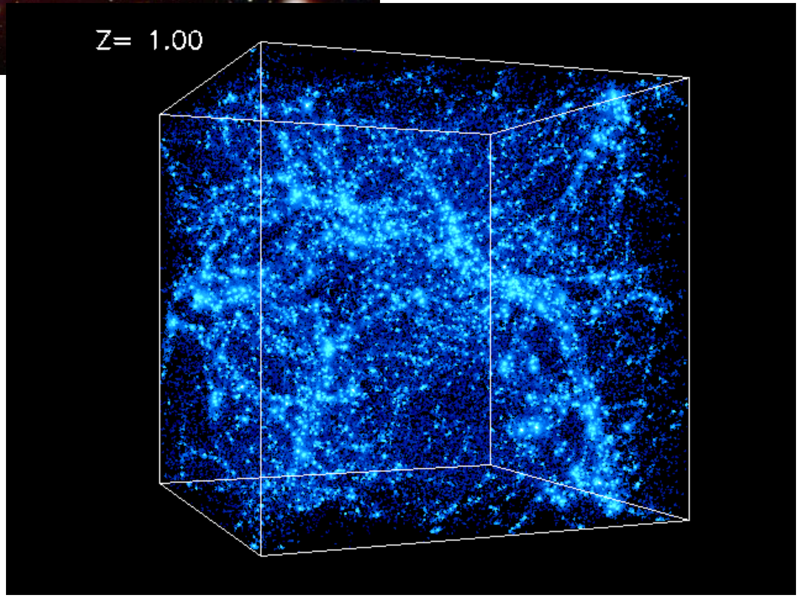












The big questions

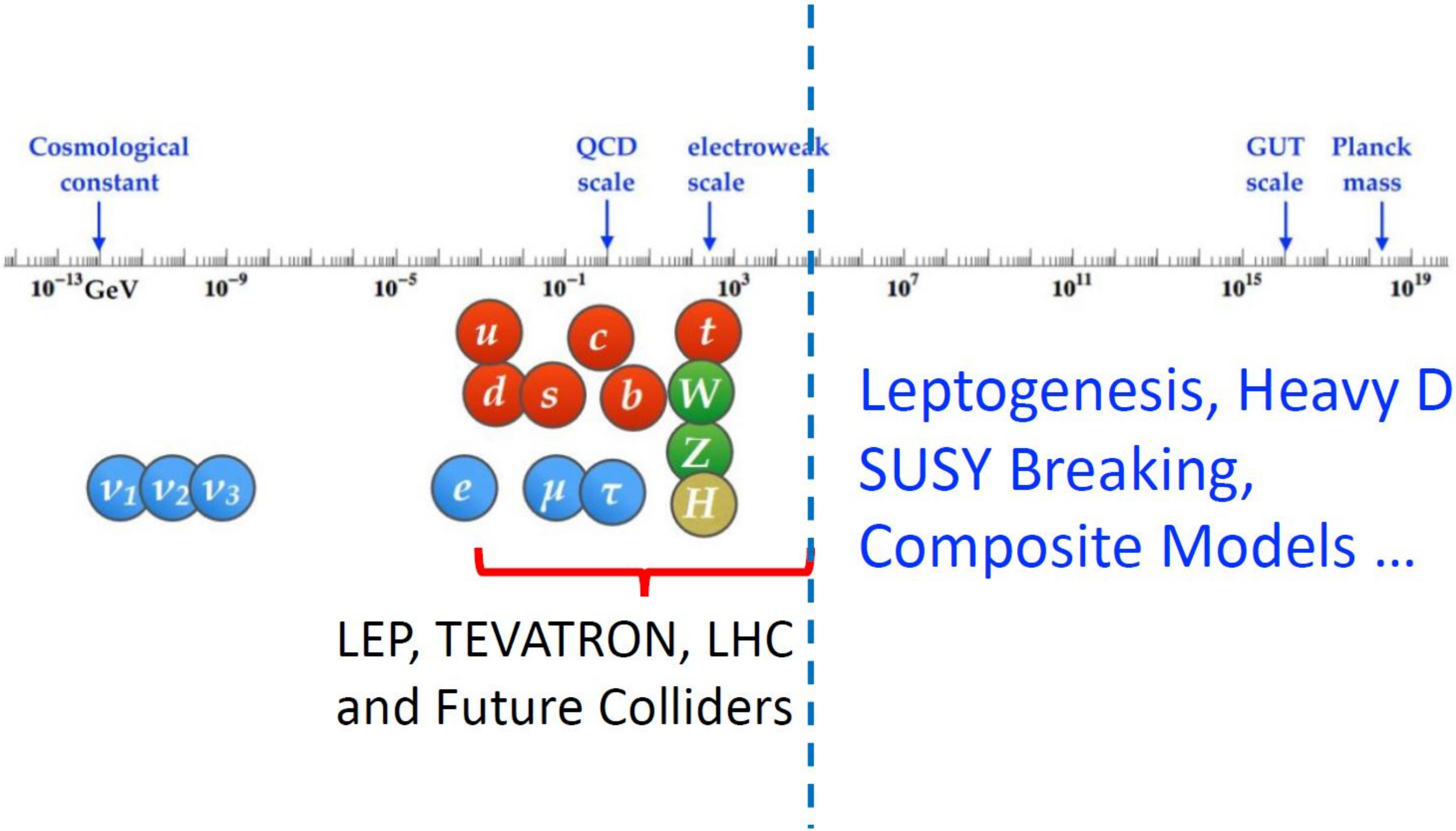
Questions in quantum field theory

1. How can gravity be quantized?
2. Why is cosmological constant so small?
3. How can the fundamental forces be unified?

Questions in Phenomenology and Cosmology

1. What are the fundamental theories for dark matter and dark energy?
2. What mechanism generated the baryon-antibaryon asymmetry?
3. What is the origin of the neutrino masses?
4. Did cosmological inflation occur? If so, what is the fundamental theory behind it?

Energy scales



Leptogenesis, Heavy DM,
SUSY Breaking,
Composite Models …

LEP, TEVATRON, LHC
and Future Colliders

The big questions

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Questions in Phenomenology and Cosmology

1. What are the fundamental theories for dark matter and dark energy?
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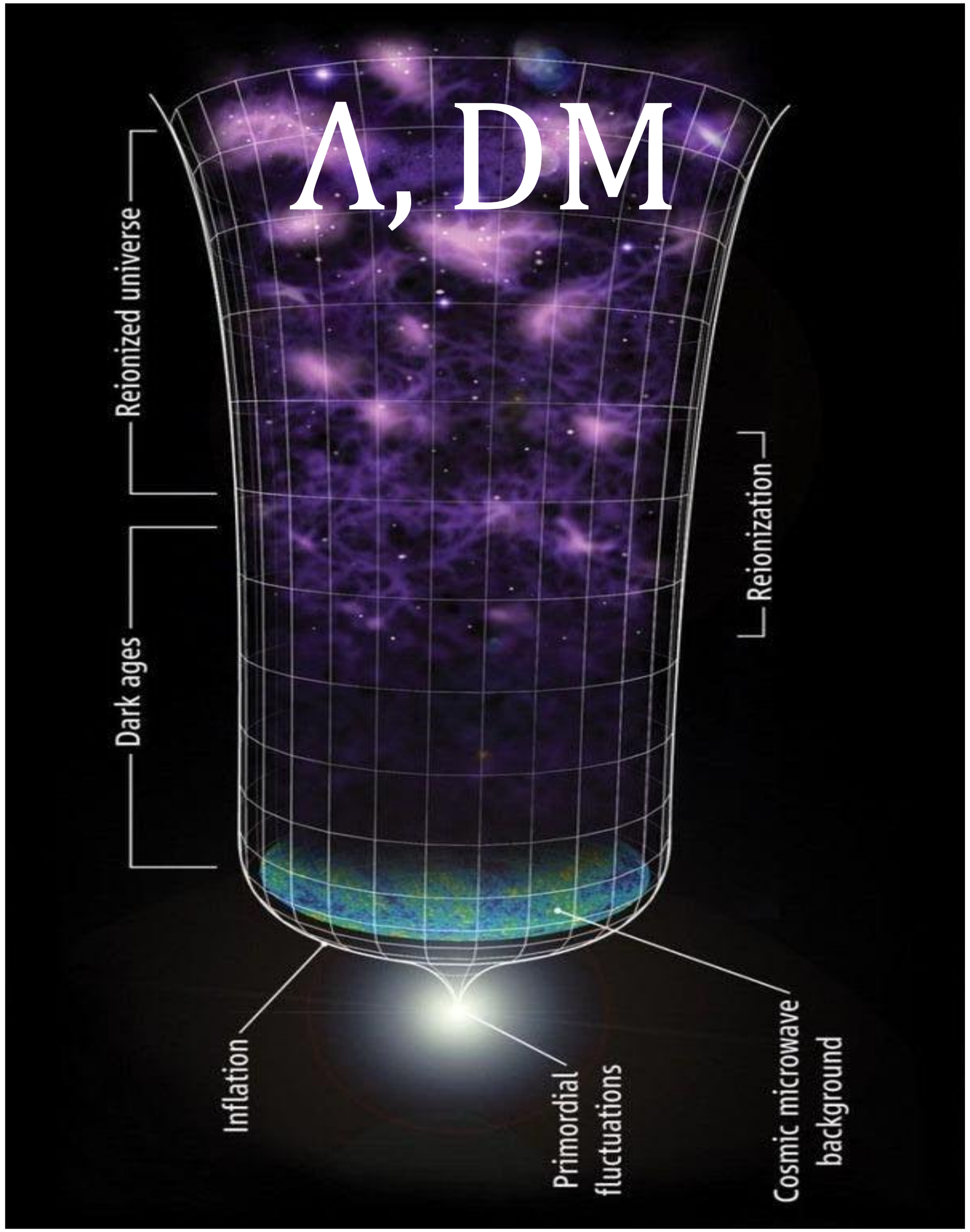
Given our short lifetimes, how can we search for evidence that may help answer these fundamental questions? How can we test whether these elegant theories are correct?

Hubble-Delayed Vacuum Decay and Its Gravitational Wave Signals

Outline

- Motivations
- GWs from a first-order phase transition
  - Strength   Frequency   Spectrum
- Standard Model vacuum decay induced by dark sector Evolution
- GWs from Standard Model vacuum decay
- Dark sector vacuum decay induced by Standard Model evolution
- Summary



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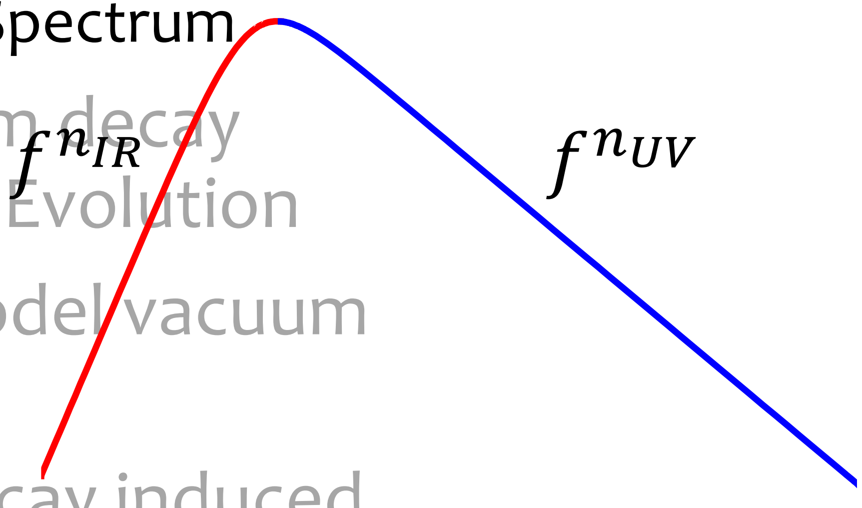

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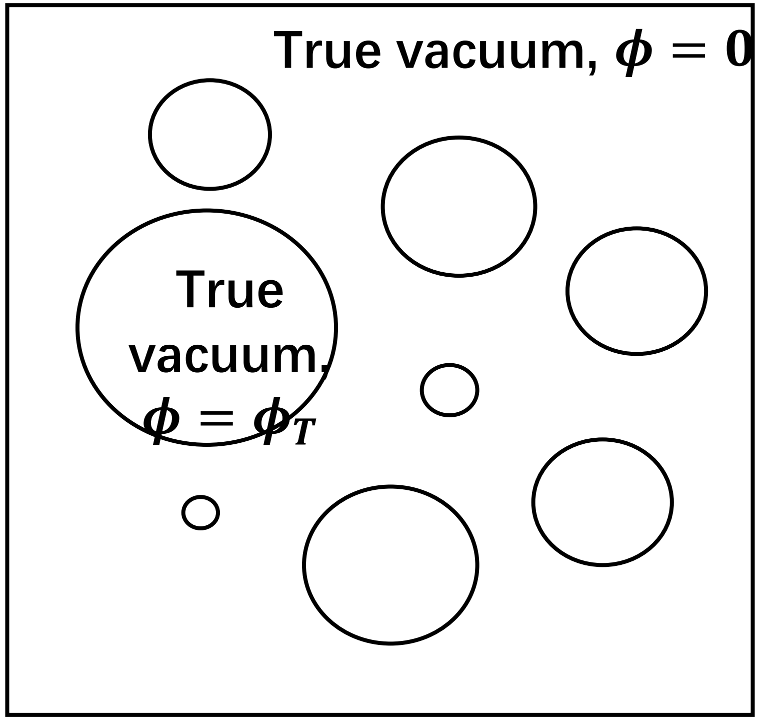

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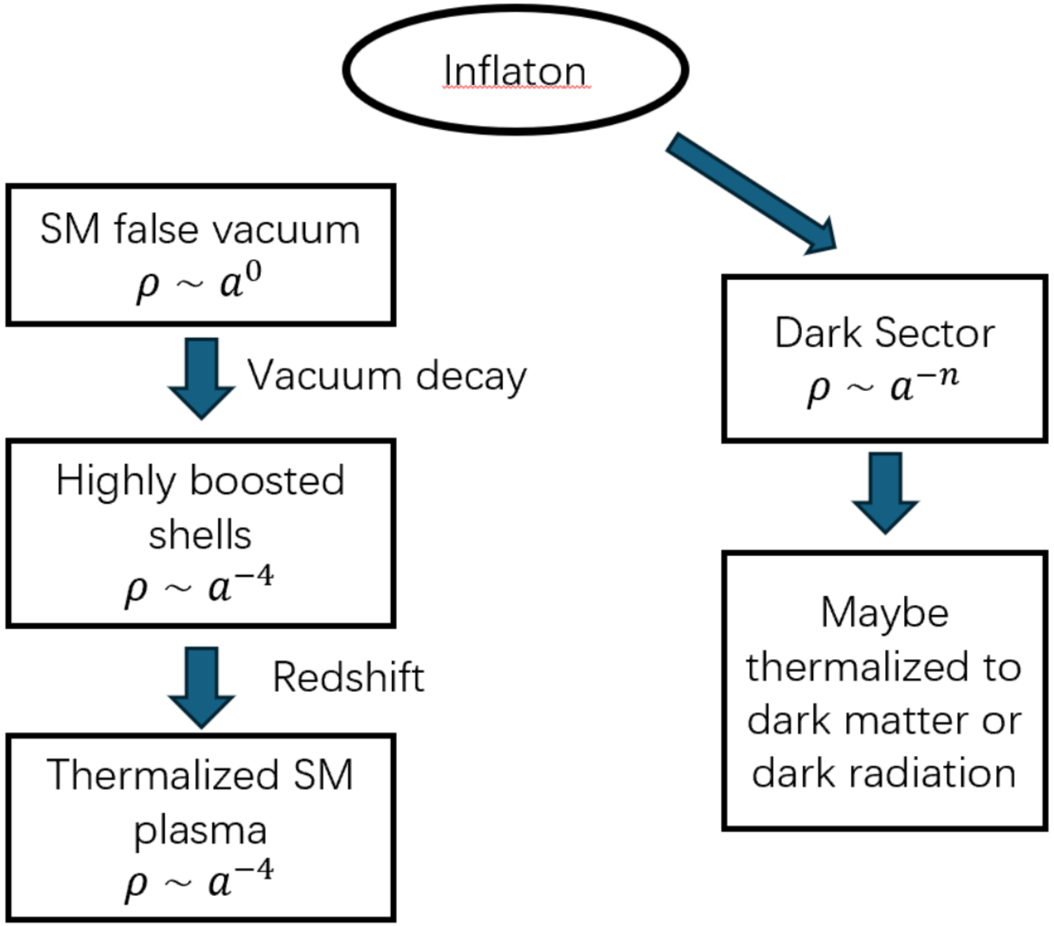

The New Origin of the Big Bang

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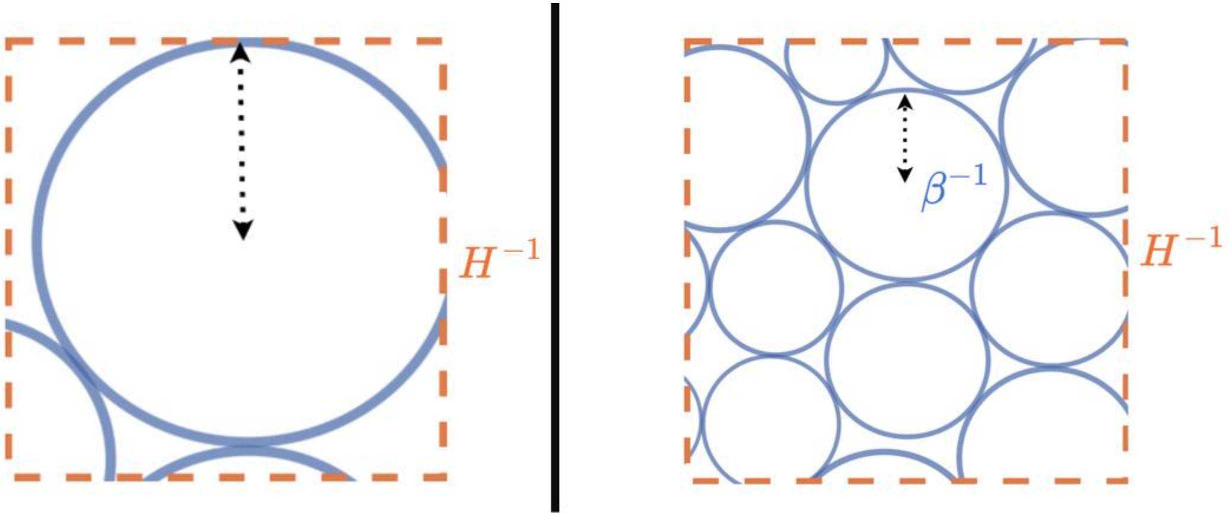

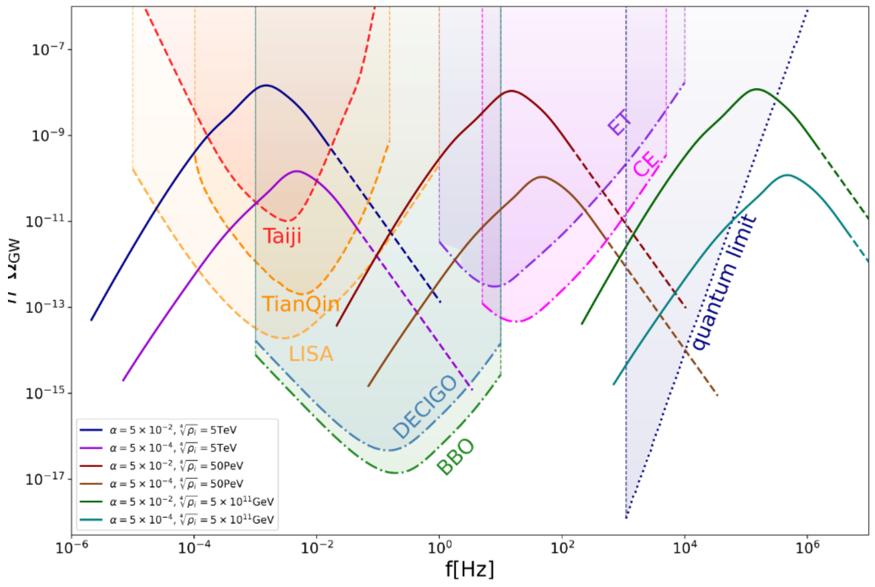

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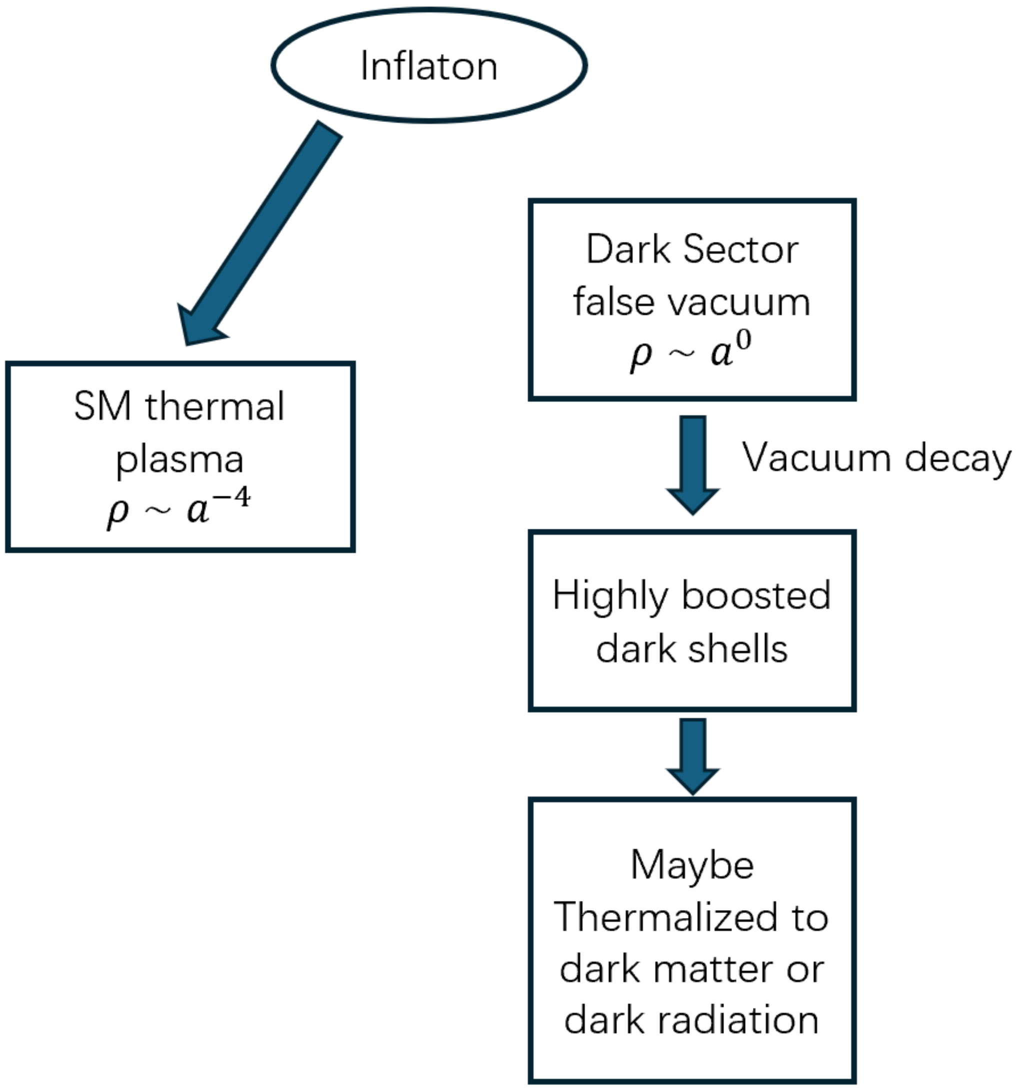

Motivations

- Phase transitions can be triggered by anything that evolves.

T

GUT scale

Seesaw scale

SUSY breaking scale

Electroweak scale

QCD scale

ϕ inflaton

Grand Unification

Baryogenesis

SUSY Breaking

Dark sector Phase transitions

…

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H

Phase transitions in any sectors that were in meta-stable state

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…

H

Phase transitions in any sectors that were in meta-stable state

This talk

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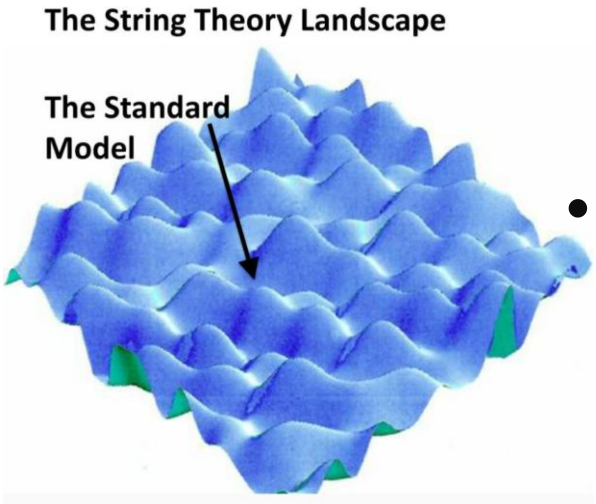
HA, Tingyu Li 2606.06587

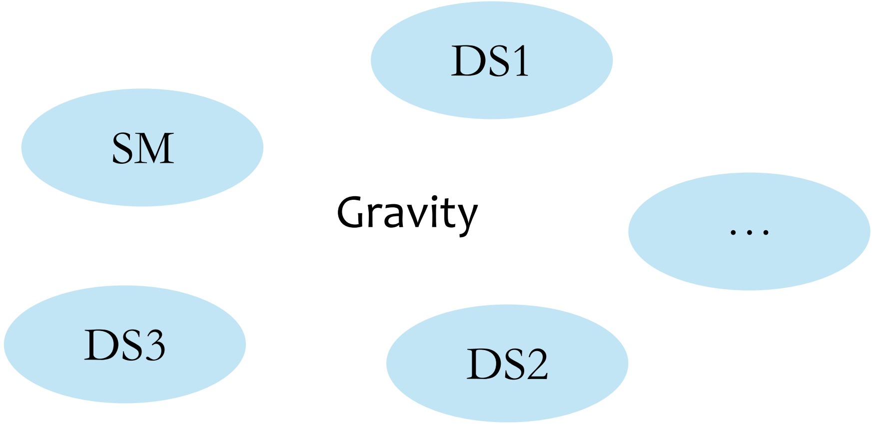
Motivations

- The **C**osmological **C**onstant problem is still the deepest mystery in theoretical physics!
- The **anthropic principle** may be the only solution.
- Landscape is required for anthropic principle to work.

- After inflation, the inflaton field reheats some of the independent sectors.



- The dark matter may only couple to the SM sector via gravity.

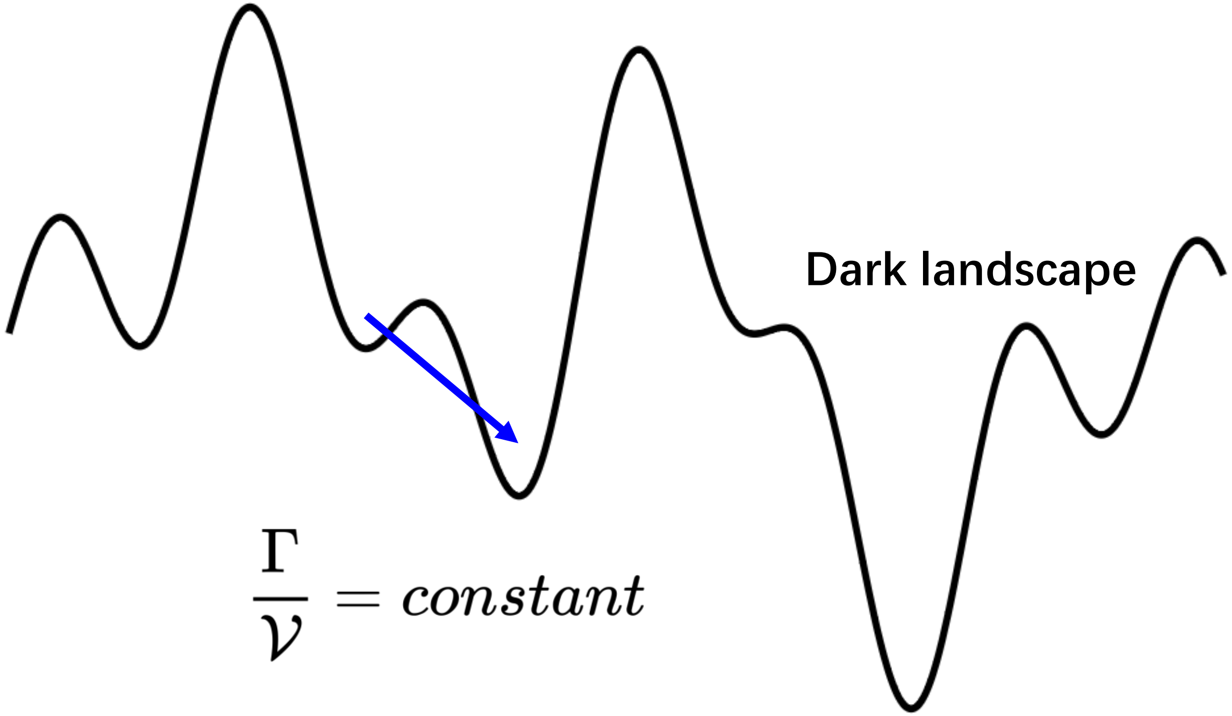


- **It is possible that each sector has an independent landscape of vacua.**

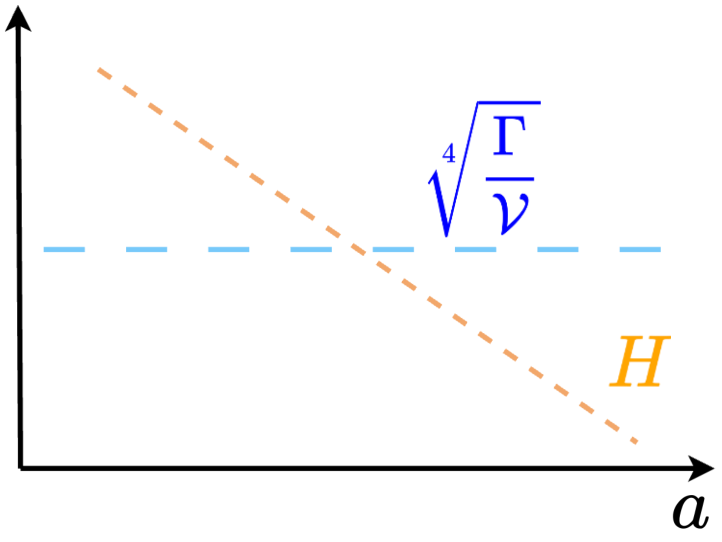
Motivations

- Meta stable vacuum decay

Phase transition condition: $\frac{\Gamma}{\mathcal{V}} \sim H^4$



$$\frac{\Gamma}{\mathcal{V}} = constant$$



- The meta stable vacuum waits for the Hubble parameter to be small enough such that the phase transition will complete.

$$H \sim \frac{\rho^{1/2}}{M_{pl}}$$

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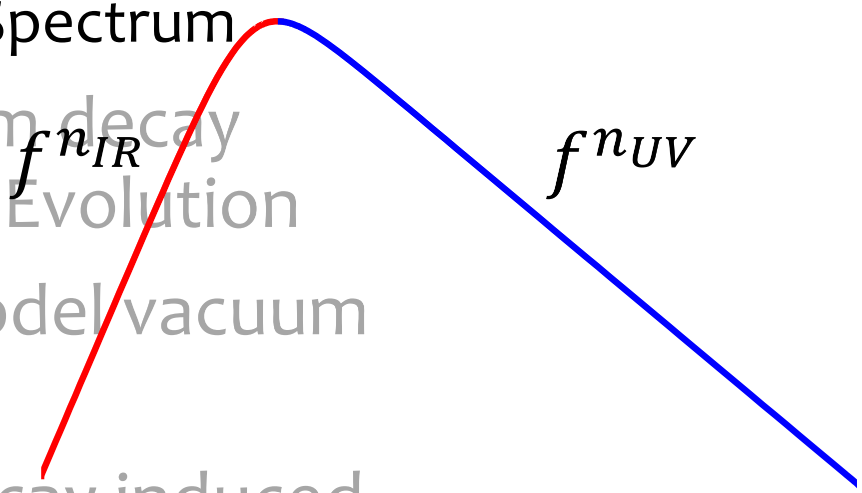
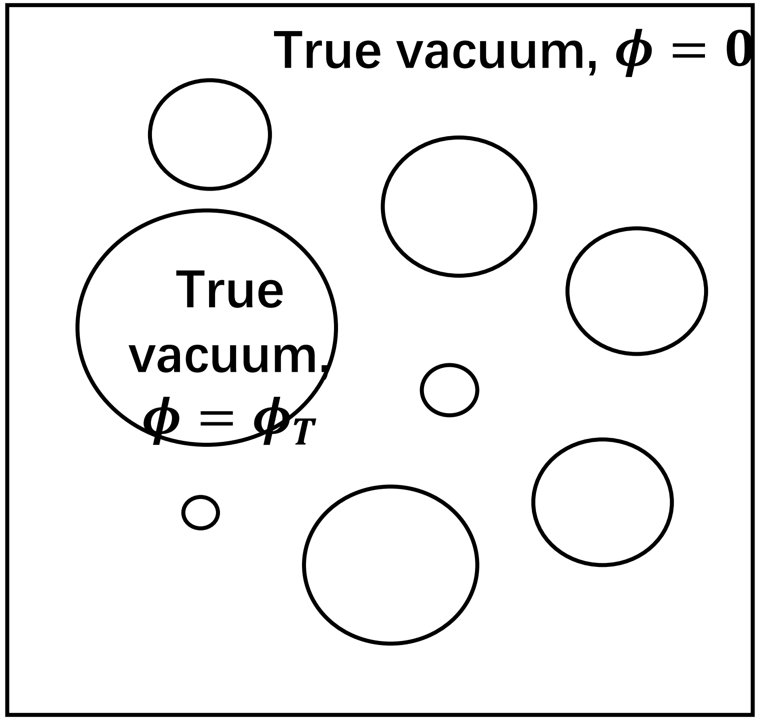
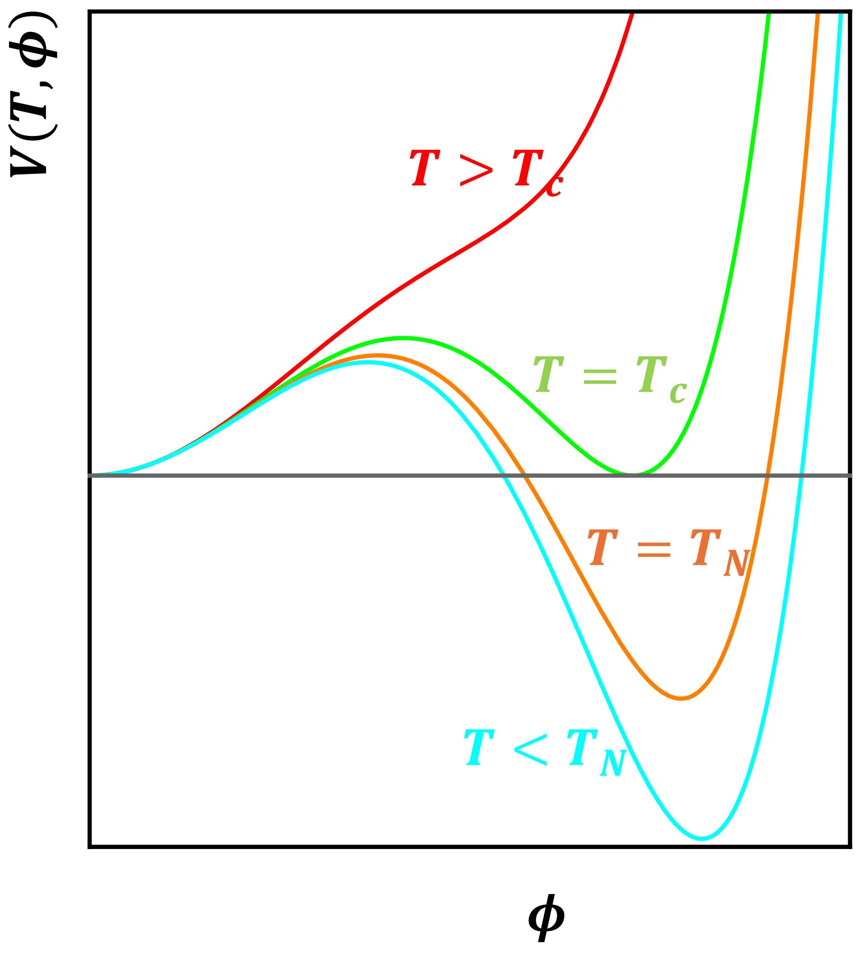




GWs from a first-order phase transition

- Phase transition starts to complete when $\Gamma/V = H^4$ at $T = T_N$.

Coleman 1977, Callan and Coleman 1977, Linde 1981



$$m^4 e^{-S}$$

$m \sim T_N$

S: bounce action

$$S = 4\ln\left(\frac{m}{H}\right)$$

$$\sim 4\ln\left(\frac{M_{pl}}{m}\right) \sim 150$$

for electroweak phase transitions

GWs from a first-order phase transition

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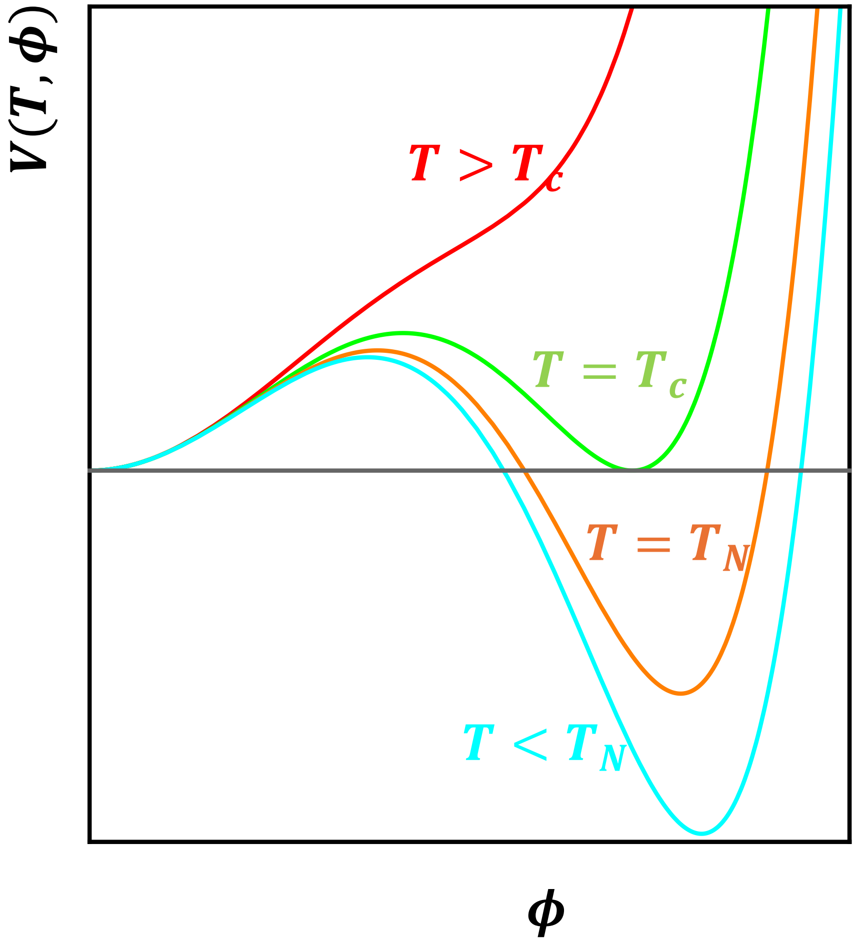
Coleman 1977, Callan and Coleman 1977, Linde 1981



$$\frac{\Gamma}{V} = m^4 e^{-S}$$

$$S \approx S(T_N) + \beta(t - t_N)$$

$\beta = -\frac{dS}{dt}$ at $T = T_N$

β determines scales of the phase transition:

(1) Phase transition completes $t \sim t_N + \beta^{-1}$.

(2) Bubble radius ~ β^{-1}.

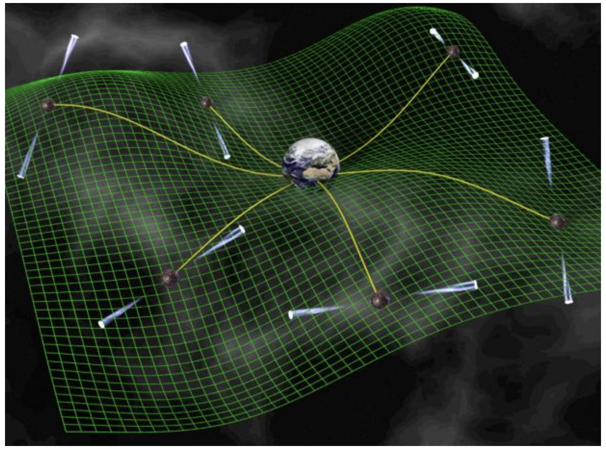
(3) GW wavelength ~ β^{-1}.

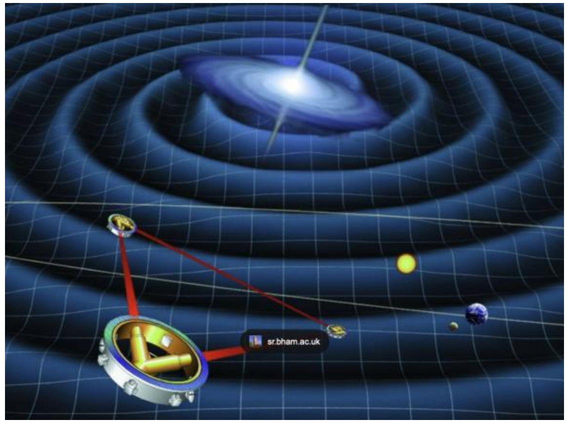
GW frequency

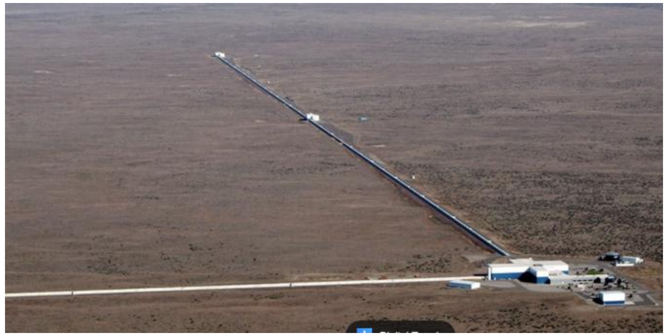
- $\beta = -\frac{dS}{dt} = -\frac{dT}{Tdt}\frac{dS}{d\log T} = H\frac{dS}{d\log T} \sim H \times S \sim 150H$ for EWPT

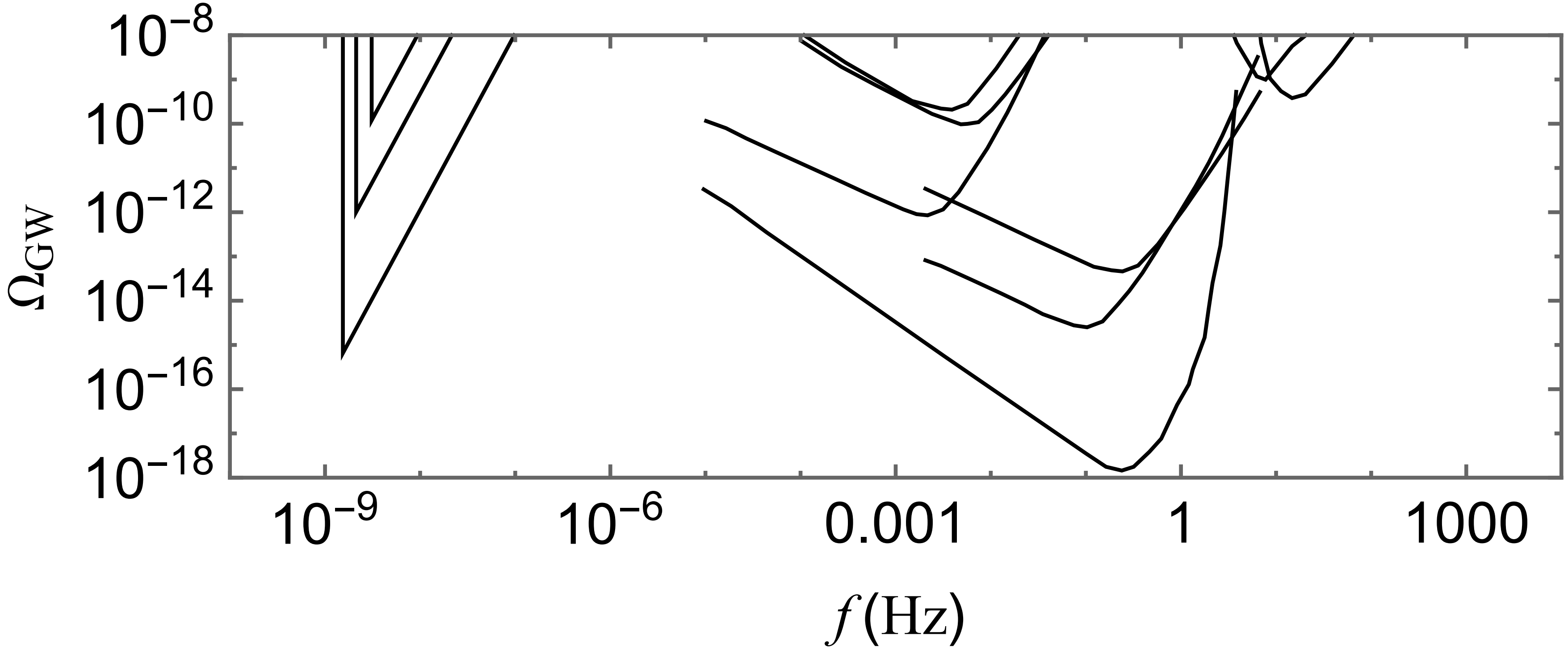
- $$\lambda_{today} \sim \lambda_{phys}\left(\frac{T_N}{T_{CMB}}\right) \sim \frac{M_{pl}}{T_N^2} \times (S(T_N))^{-1} \times \underbrace{\frac{T_N}{T_{CMB}} \sim 10^7\ \mathrm{km} \times \left(\frac{1\ \mathrm{TeV}}{T_N}\right)}_{\text{LISA, TAIJI, TIANQIN}}$$

GW detectors





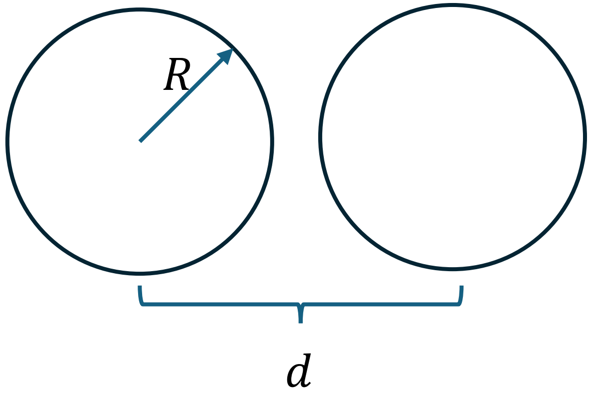




GW strength

- The metric around flat space-time $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- The gravitational waves are in h_{ij}^{TT}, the traceless and transverse part of h_{ij}.
- The gravitational potential are in h_{00}.
- In a relativistic system, we can use h_{00} to estimate h_{ij}^{TT}.
- The GW strength is controlled by:

$$\beta \sim H \times S \text{ and } \alpha = \frac{L}{\rho}$$



$$R \sim d \sim \beta^{-1}$$

$$M \sim R^3 L$$

Latent heat density

$$V \sim R^3$$

$$\Phi \sim GM/R$$

$$\rho_{GW} \sim \rho_0 \sim \frac{\Phi M}{V} \sim \frac{GM^2}{R^4} \sim GL^2R^2 \sim \frac{GL^2}{\beta^2}$$

$$\Omega_{GW} = \Omega_R \times \frac{\rho_{GW}}{\rho_R} \sim \Omega_R \times \frac{GL^2}{\beta^2 \rho_R} \sim \Omega_R \times \frac{H^2}{\beta^2} \times \frac{L^2}{\rho_R^2}$$

$$\Omega_R \approx 10^{-5}$$

In RD: $H^2 \sim G\rho_R$

GW strength

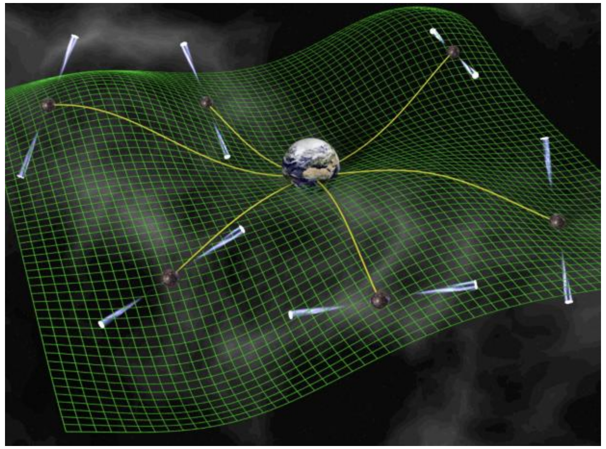
- The metric around flat space-time $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- The gravitational waves are in h_{ij}^{TT}, the traceless and transverse part of h_{ij}.
- The gravitational potential are in h_{00}.
- In a relativistic system, we can use h_{00} to estimate h_{ij}^{TT}.
- The GW strength is controlled by:

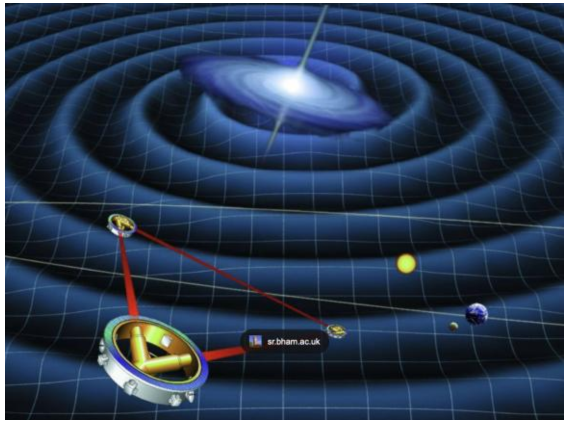
$$\rho_{\mathrm{GW}} \sim \frac{GM^2}{R^4} \sim \frac{G\Delta\rho^2}{\beta^2} \qquad H^2 \sim G\rho_R$$

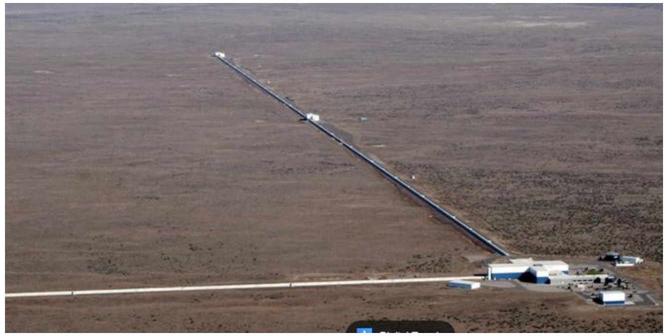
$$\Omega_R \approx 10^{-5}, \frac{H}{\beta} \approx 0.01, \frac{\Delta\rho}{\rho} \approx 1$$

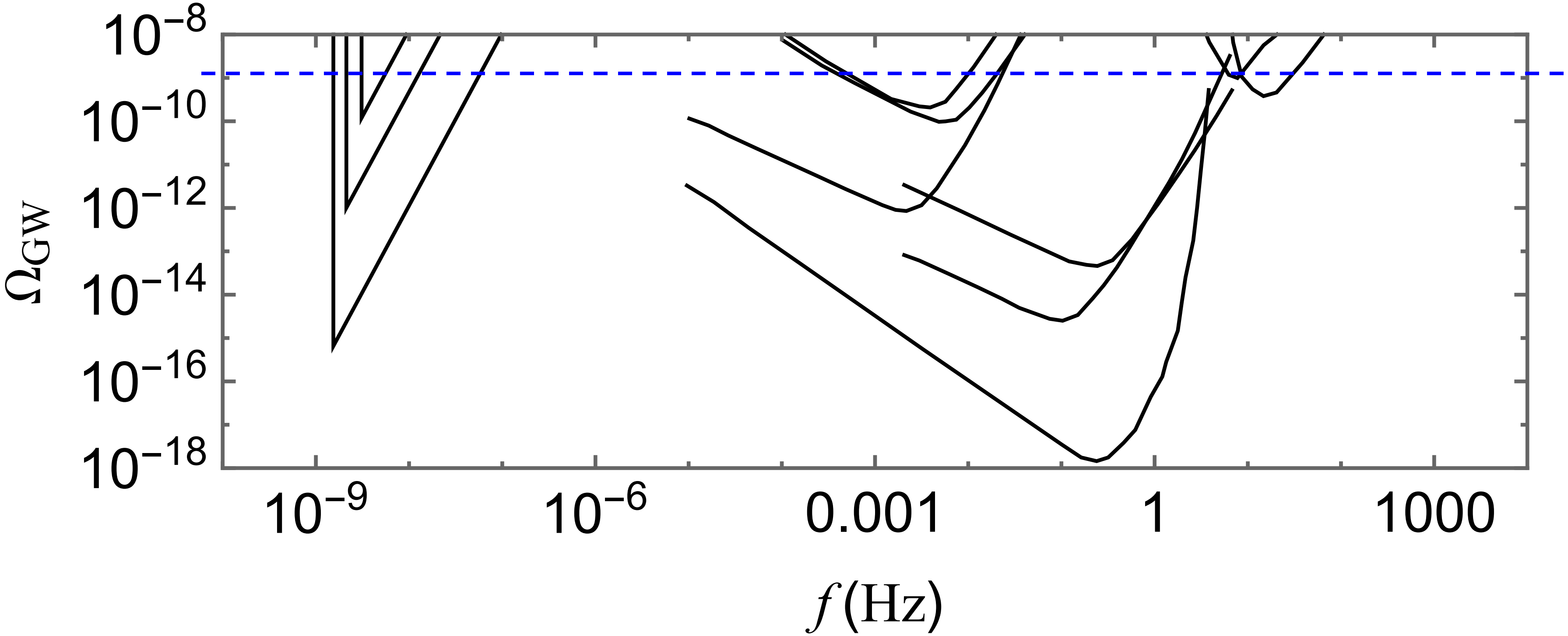
$$\Omega_{\mathrm{GW}} = \Omega_R \times \frac{\rho_{\mathrm{GW}}}{\rho_R} \sim \Omega_R \times \frac{H^2}{\beta^2} \times \frac{\Delta\rho^2}{\rho_R^2} \approx \mathbf{10^{-9}}$$

GW detectors









GW spectrum

- The metric in comoving coordinate with conformal time:

$$ds^2 = a^2(\eta)(-d\eta^2 + (\delta_{ij} + h_{ij})dx^i dx^j)$$

- The linearized Einstein Equation:

$$h''_{\boldsymbol{k},\lambda} + 2\mathcal{H}h'_{\boldsymbol{k},\lambda} + k^2 h_{\boldsymbol{k},\lambda} = 16\pi G a^2 e^{ij}_{\lambda} \Lambda^{ab}_{ij}(\hat{k}) T_{ab,\boldsymbol{k}},$$

- The solution to the linearized Einstein Equation:

$$\mathrm{h}_{+,\times}(\eta, \mathbf{k}) = 16\pi G \int_{-\infty}^{\infty} \mathrm{d}\eta' \, G\left(\eta, \eta', \mathbf{k}\right) \, a\left(\eta'\right) \, T_{+,\times}\left(\eta', \mathbf{k}\right)$$

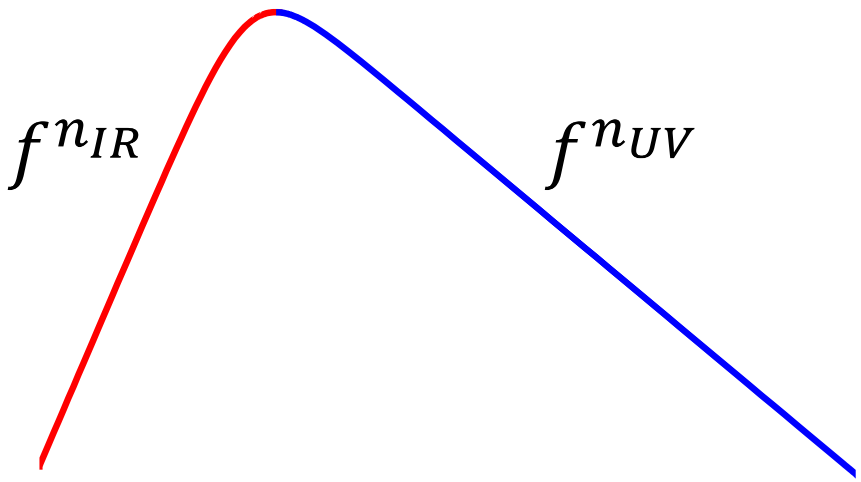
GW spectrum

GW energy density

$$\Omega_{\rm GW}(k) = \frac{k^3}{12\pi^2 a^4 H^2 M_{\rm Pl}^4} \int_0^\eta d\eta_1 \int_0^\eta d\eta_2 \; a^3(\eta_1) a^3(\eta_2)$$
$$\times \cos k(\eta_1 - \eta_2) \Lambda_{ab}^{cd}(\hat{k}) \langle T_{\boldsymbol{k}}^{ab}(\eta_1) T_{cd,\boldsymbol{p}}^*(\eta_2) \rangle'_{\boldsymbol{p}=\boldsymbol{k}} \, .$$

$\beta^{-1} \ll H^{-1}$

- $a(\eta)$ does not change much during the phase transition.
- T_{ab} vanishes for $t > t_N + \beta^{-1}$.
- For $k_{phys} < \beta$, the η_1, η_2 integral is independent of k.
- $n_{IR} = 3$, almost independent of the details of the phase transition model.



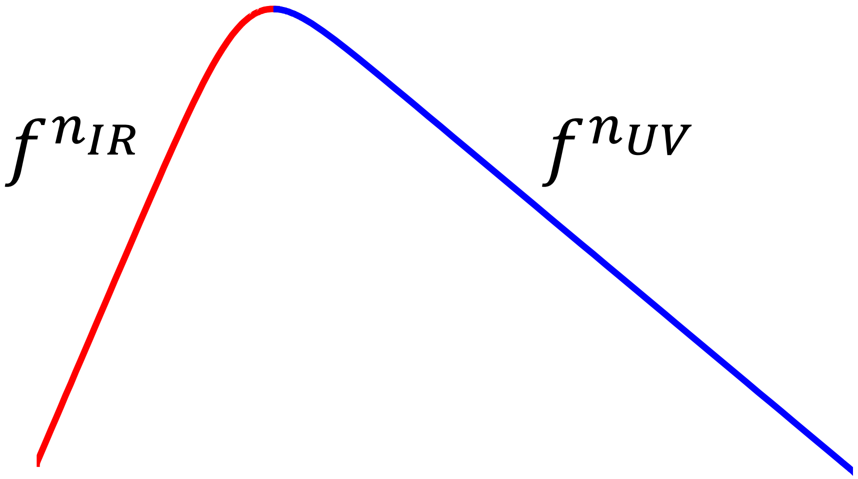
Summary of GW properties produced in RD

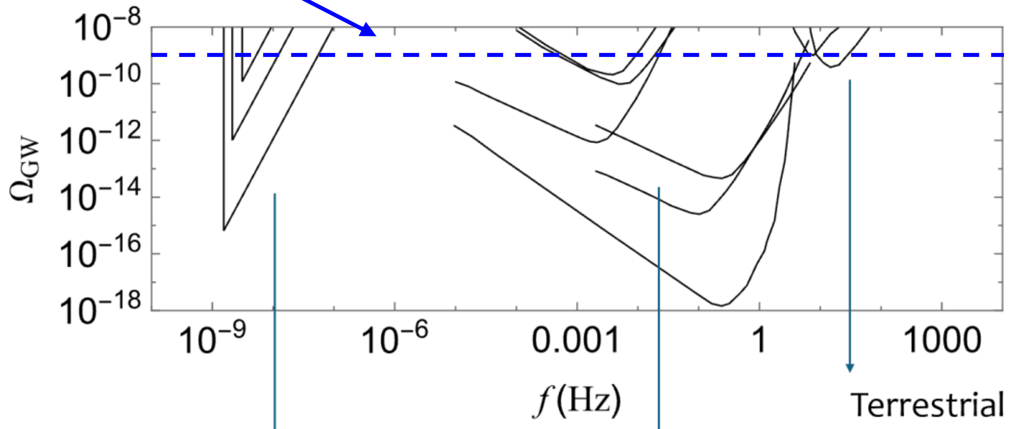
- $\lambda_{today} \sim \lambda_{phys}\left(\frac{T_N}{T_{CMB}}\right) \sim \frac{M_{pl}}{T_N^2} \times \left(\frac{S_3(T_N)}{T_N}\right)^{-1} \times \frac{T_N}{T_{CMB}} \sim 10^7\ \mathrm{km} \times \left(\frac{1\ \mathrm{TeV}}{T_N}\right)$

for EWPT

- $\Omega_{\mathrm{GW}} = \Omega_R \times \frac{\rho_{\mathrm{GW}}}{\rho_R} \sim \Omega_R \times \frac{H^2}{\beta^2} \times \frac{\Delta\rho^2}{\rho_R^2} \approx \mathbf{10^{-9}}$

- $n_{IR} = 3$





Pulsar timing arrays: IPTA, NanoGrav, CPTA …

Space GW detectors: LISA, TAIJI, TIANQIN, DECIGO, BBO …

Terrestrial detectors: Cosmic explorer, Einstein Telescope …

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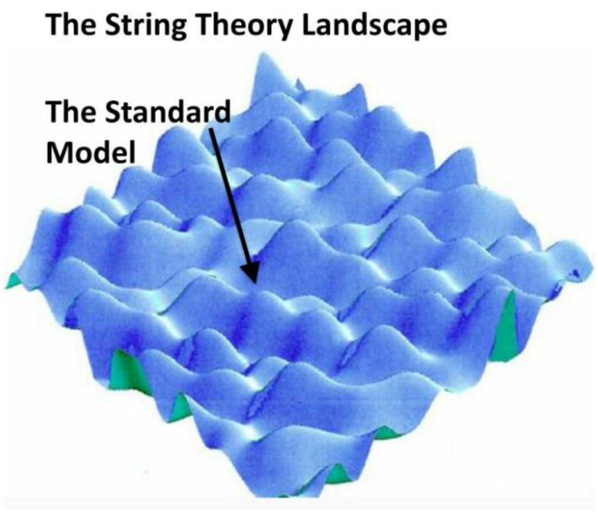
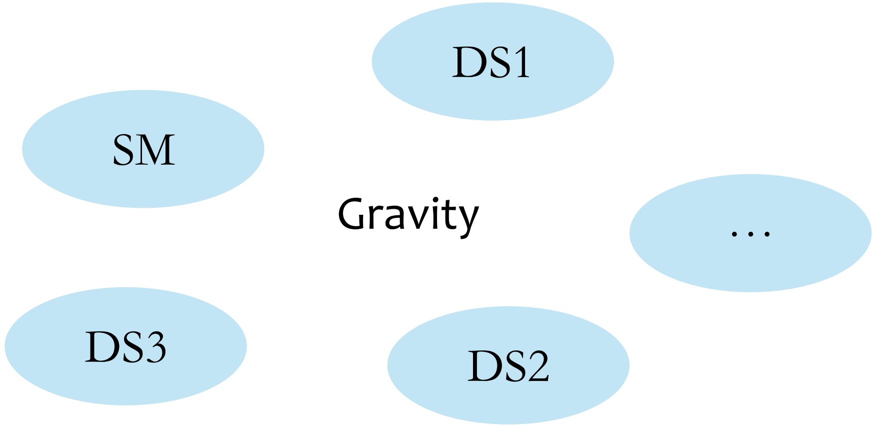
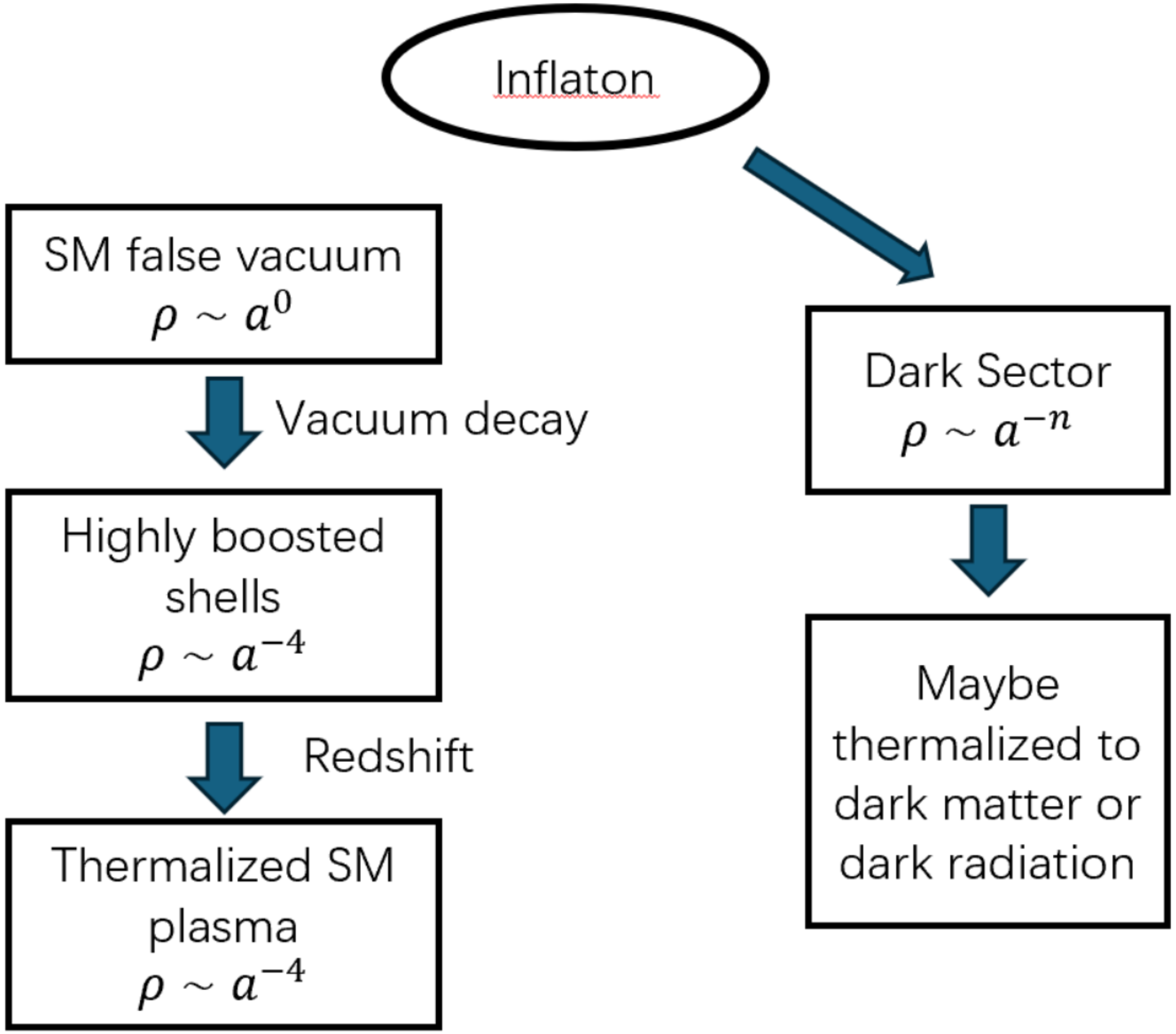
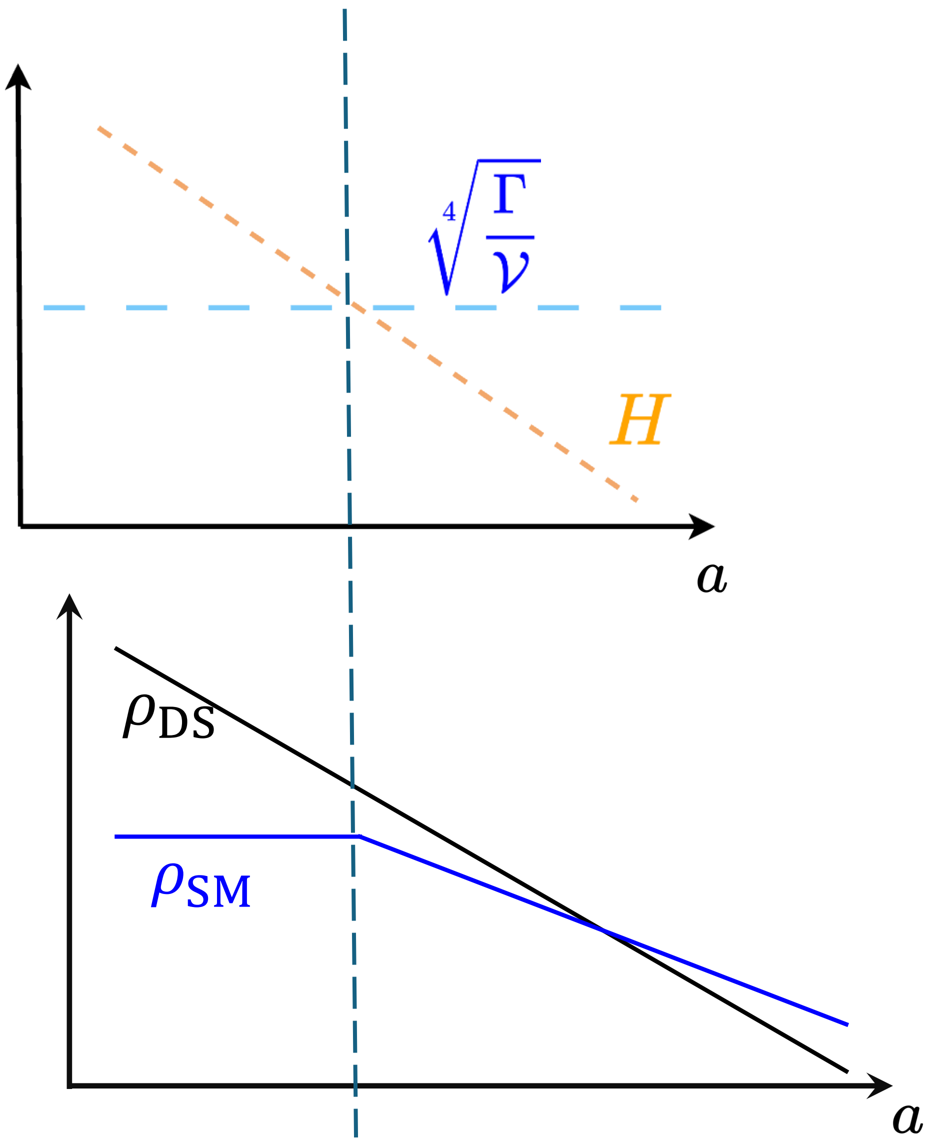




SM vacuum decay induced by DS evolution





The New Origin of the Big Bang

Constraints

- N_{eff}, the effective neutrino number:
  - CMB bound: $N_{\text{eff}} \simeq 3.0 \pm 0.17$

  Additional N_{eff} can

  (1) Reduce the sound horizon

  (2) Change the photon diffusion damping

  (3) Delays matter-radiation equity

  (4) Change the neutrino free-streaming length

  - BBN bound: $N_{\text{eff}} \simeq 2.9 \pm 0.3$

  Additional radiation can change the primordial helium and deuterium abundances.

$$\rho_{\text{rad}} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right]$$

$$N_{\text{eff}}^{\text{SM}} \simeq 3.044$$

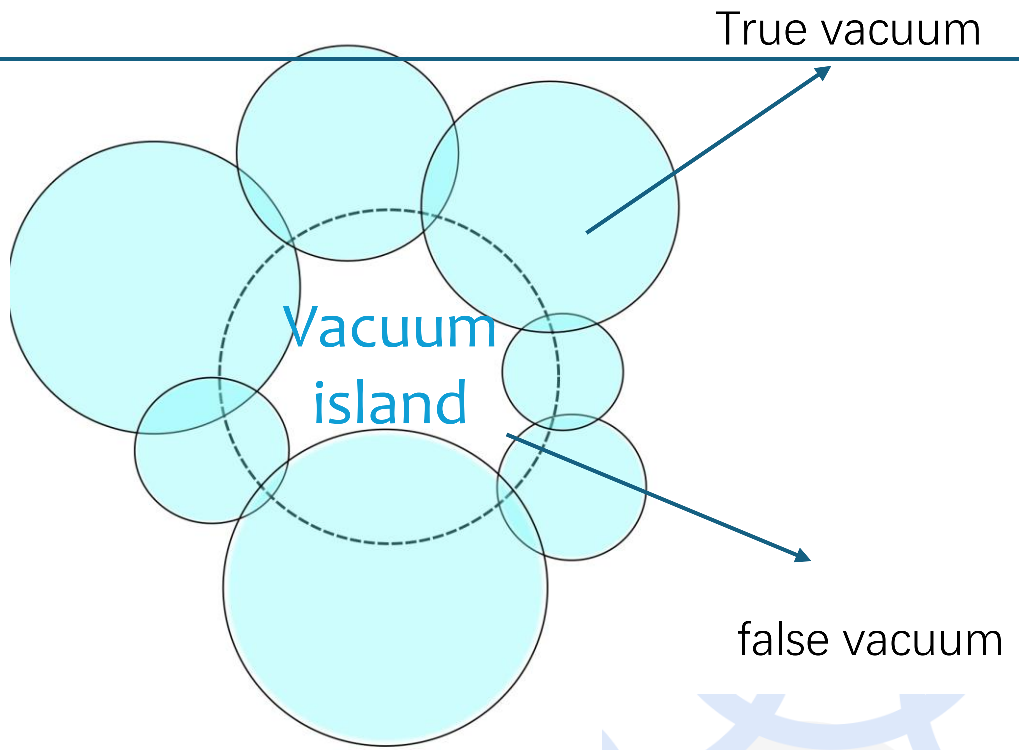
$$N_{\text{eff}}^{\text{CMB}} \simeq 3.0 \pm 0.17$$

$$N_{\text{eff}}^{\text{BBN}} \simeq 2.9 \pm 0.3$$

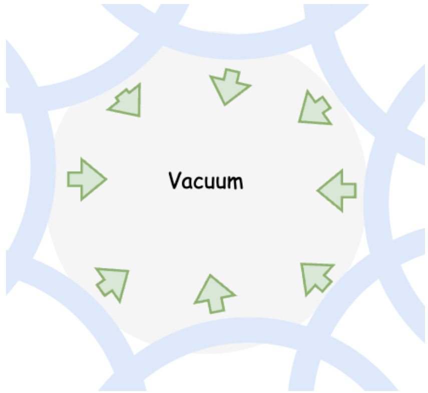
$$\Delta\rho_{\text{rad}} < 5\% \times \rho_{\text{SM}} \qquad (2\sigma)$$

Constraints

- Primordial black holes
  - Bubbles nucleate randomly in the spacetime.
  - Vacuum islands form randomly.
  - Outside the vacuum island: $\rho \sim a^{-4}$.
  - Inside the vacuum island: $\rho \sim a^{0}$.
  - If the vacuum island can survive for a long time or if the latent energy density is too large, it will collapse into a blackhole.
  - To many black holes overclose the Universe.



$$\alpha = \frac{\rho_{\mathrm{SM}}}{\rho_{\mathrm{tot}}} < 0.05$$

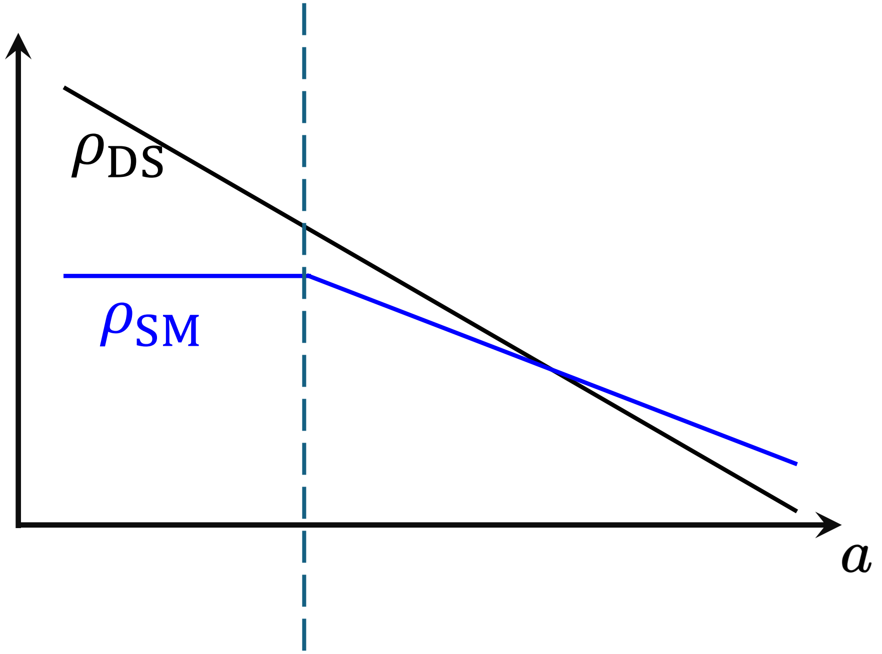


Formation of vacuum isleand

Dark sector equation of state

- During phase transition $\rho_{\rm DS} \gg \rho_{\rm SM}$ (PBH bound).
- Energy in DS today must satisfy the $\Delta N_{\rm eff}$ bound ➡ Today, $\rho_{\rm DS} \ll \rho_{\rm SM}$

$$\rho_{\rm DS} \propto a^{-n} \text{ with } n > 4.$$



- It can be achieved. However, to my knowledge **only** kination (n=6) model is "well-motivated".

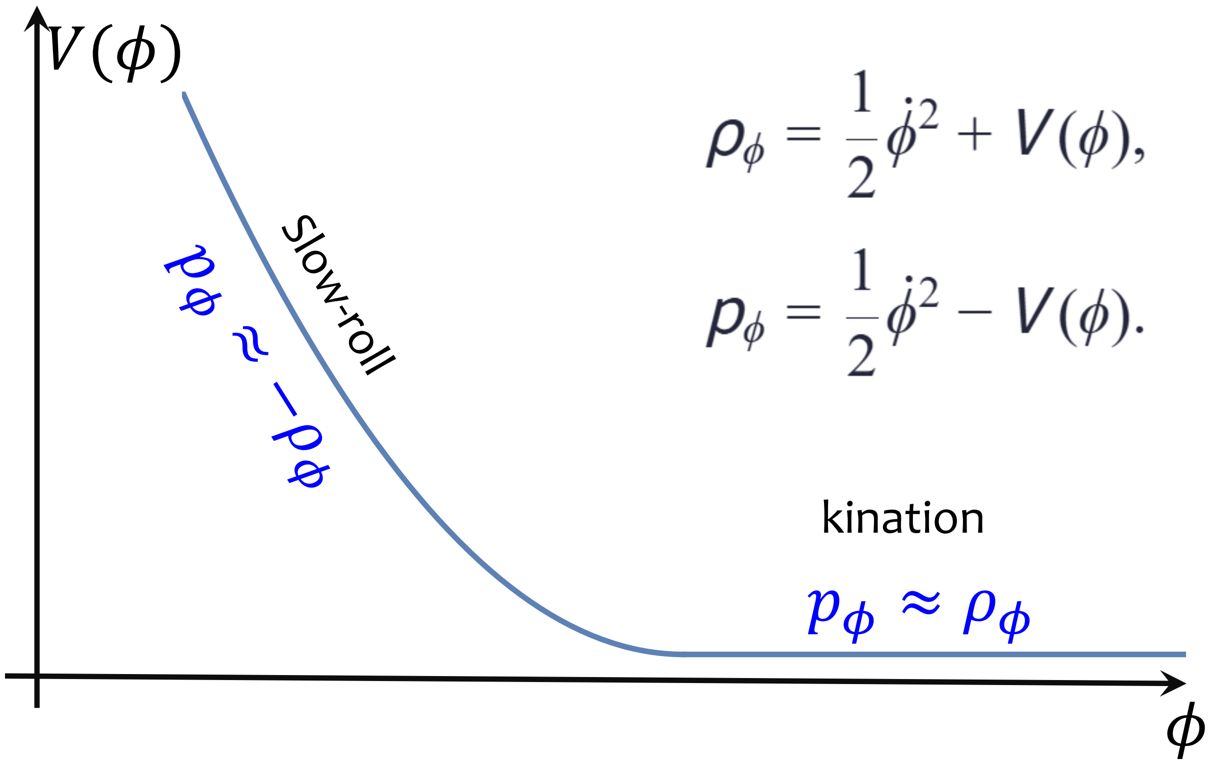
Spokoiny PLB 1993, Joyce PRD 1997, Peebles and Vilenkin PRD 1999

- The most natural way to realize kination domination is to make it happen right after inflation.

Simplest realization of kination domination

- The inflaton field potential becomes flat right after the end of inflation.
- Inflaton field transits all its energy into its kinetic energy.
- $p_\phi \approx \rho_\phi$
- $n = 6$ (Friedmann equations)

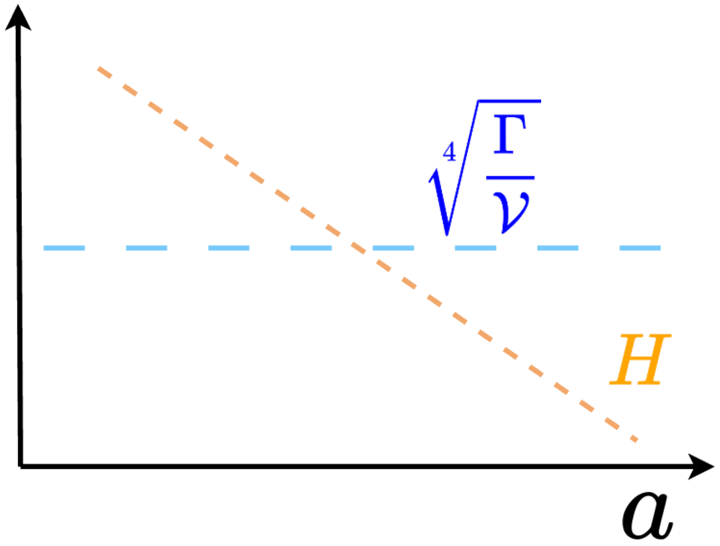
$$\dot{\rho} + 3H(\rho + p) = 0$$
$$\rho \approx p$$
$$\frac{d\rho}{\rho dt} + \frac{6da}{adt} = 0$$
$$\rho \sim a^{-6}$$



$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi),$$
$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi).$$

Evolution of the bubbles in Hubble delayed PT

- No concept of β
- $\dot{H}/H \sim H$
- Bubble radius $\sim H^{-1}$



Hubble delayed PT:

$$\frac{\Gamma}{\mathcal{V}} = constant$$

(No fluid, no plasma)

Thermal PT:

$$\frac{\Gamma}{\mathcal{V}} \sim \exp(\beta t)$$

Phase transition condition:

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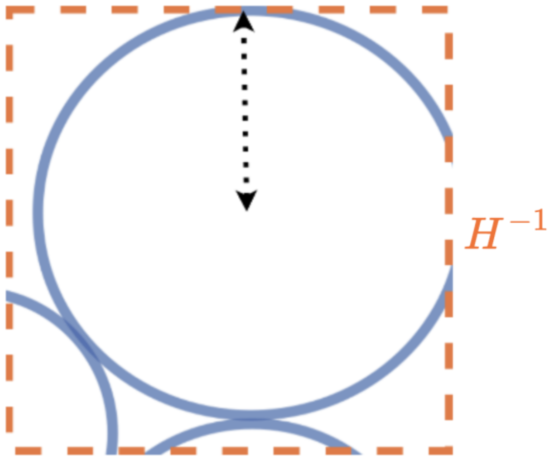
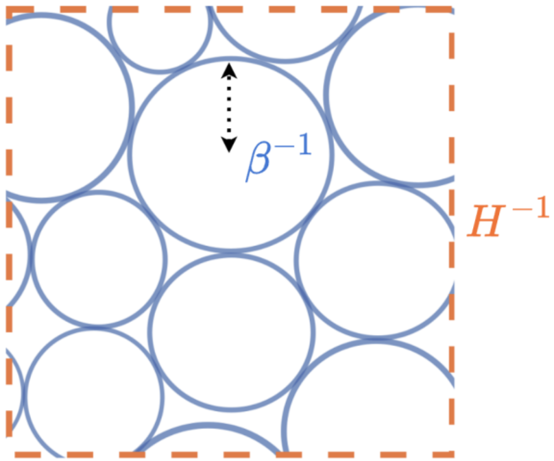
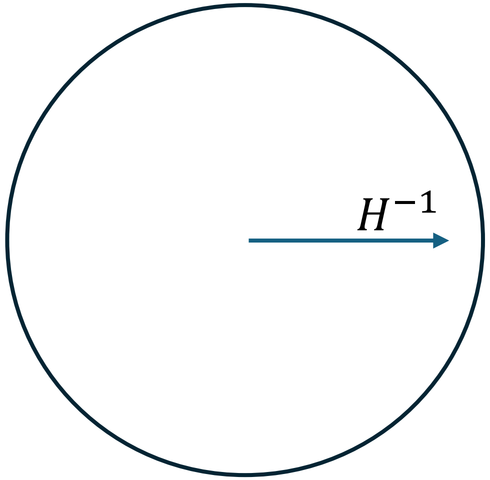




Evolution of the bubbles in Hubble delayed PT

- No plasma or fluid
- No frictions to bubble expansion
- The boost can be very large
- The walls are very thin.



- Boost: $\gamma \sim \frac{\Delta\rho^{\frac{1}{4}}}{H} \sim \left(\frac{\Delta\rho}{\rho}\right)^{\frac{1}{4}} \frac{M_{pl}}{T} \sim 10^{15} \left(\frac{\Delta\rho}{\rho}\right)^{\frac{1}{4}}$ (EW)

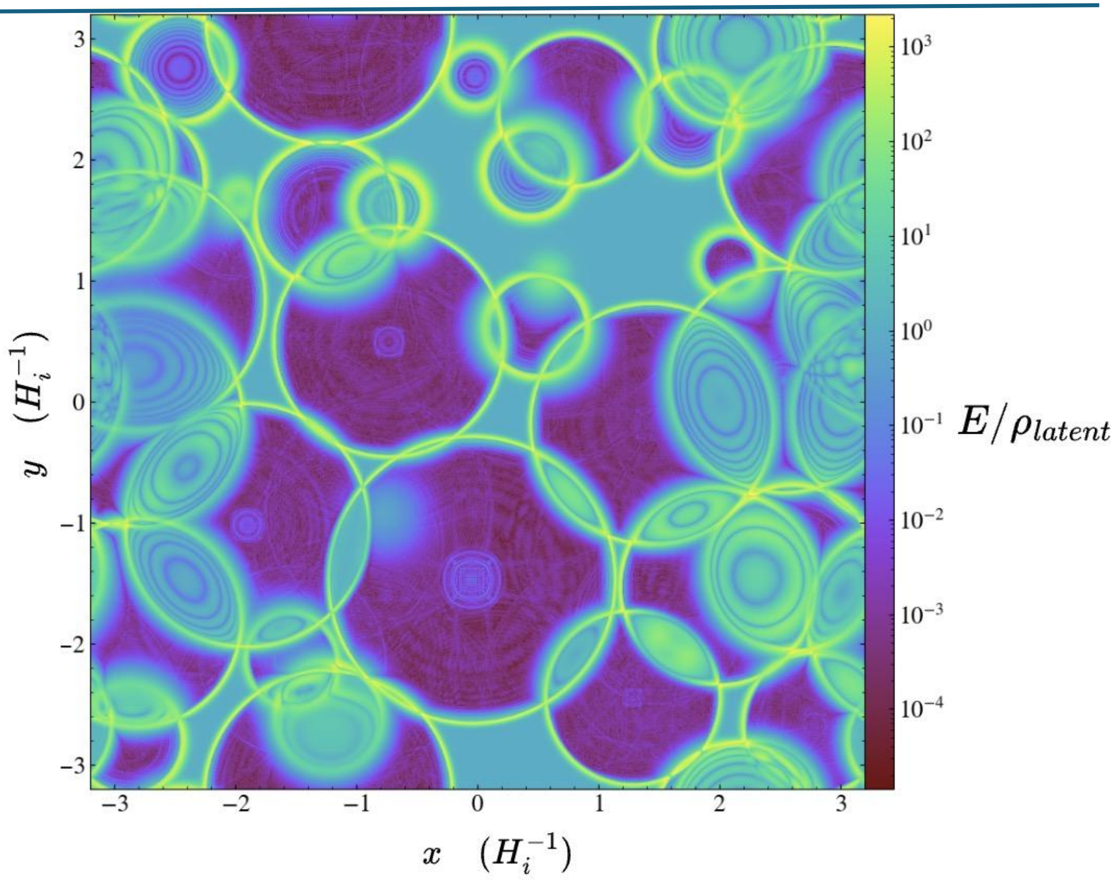
- The characteristic energy of each particle in the walls approaches M_{pl}.

Bubble evolution after collisions

- Long lived shell structure after collision
- EoM of the scalar field:

$$\frac{\partial^2\phi}{\partial\eta^2} + 2\mathcal{H}\frac{\partial\phi}{\partial\eta} - \frac{1}{r}\frac{\partial^2}{\partial r^2}(r\phi) + a^2\frac{\mathrm{d}V}{\mathrm{d}\phi} = 0$$

γ^2 γ^1 γ^2 γ^0



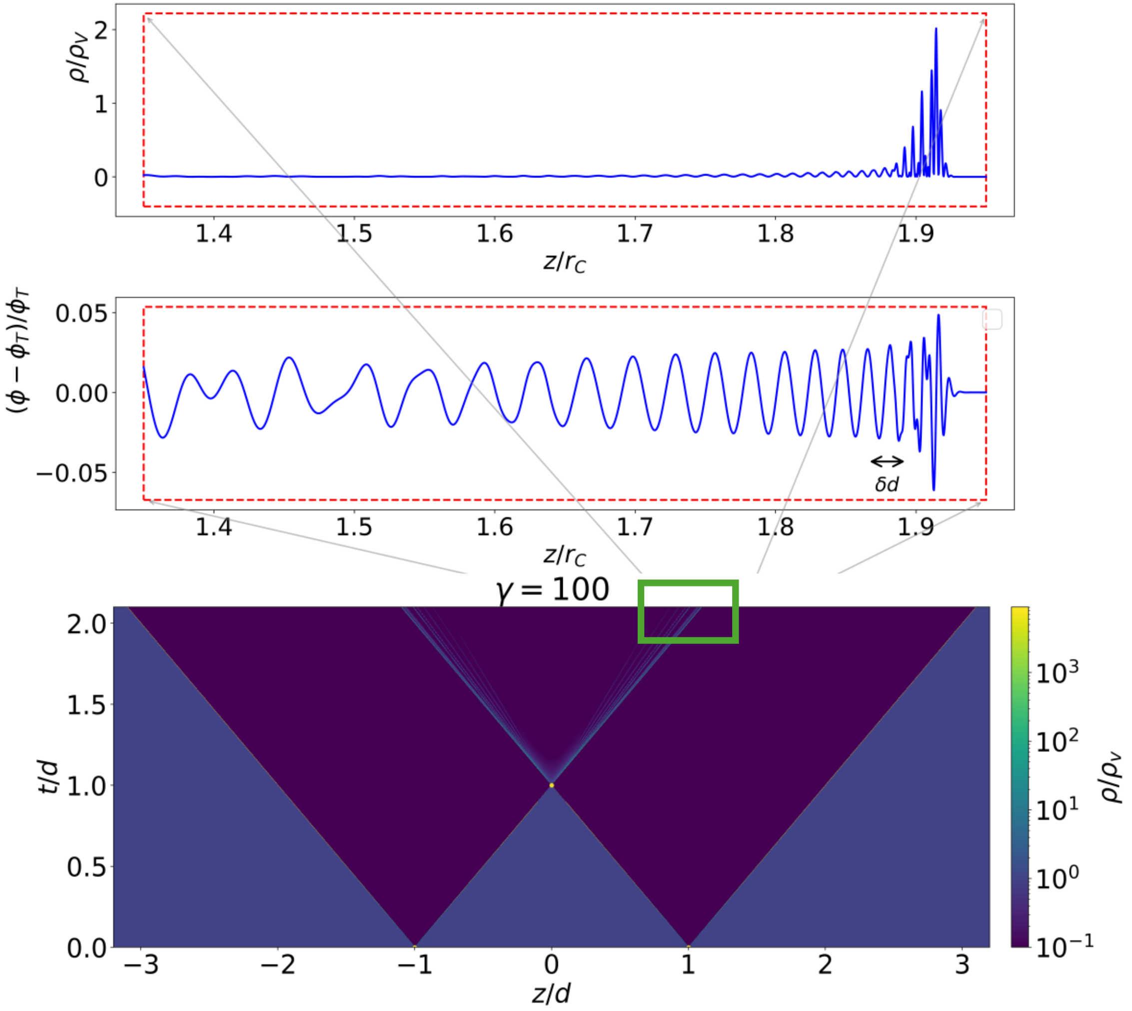
- The shells still form spherical structures.
- Potential terms are negligible.
- High energy shells go through each other in subsequent collisions.

Thermalization is very slow with scalar potential interactions.

Properties of the GWs from DS vacuum decay

- Long lived shell structure after collision
- EoM of the scalar field:

$$\underset{\gamma^2}{\frac{\partial^2\phi}{\partial\eta^2}} + \underset{\gamma^1}{2\mathcal{H}\frac{\partial\phi}{\partial\eta}} - \underset{\gamma^2}{\frac{1}{r}\frac{\partial^2}{\partial r^2}(r\phi)} + \underset{\gamma^0}{a^2\frac{\mathrm{d}V}{\mathrm{d}\phi}} = 0$$



- The shells still form spherical structures.
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- High energy shells go through each other

Thermalization is very slow with scalar potential interactions.

Thermalization with gauge interactions

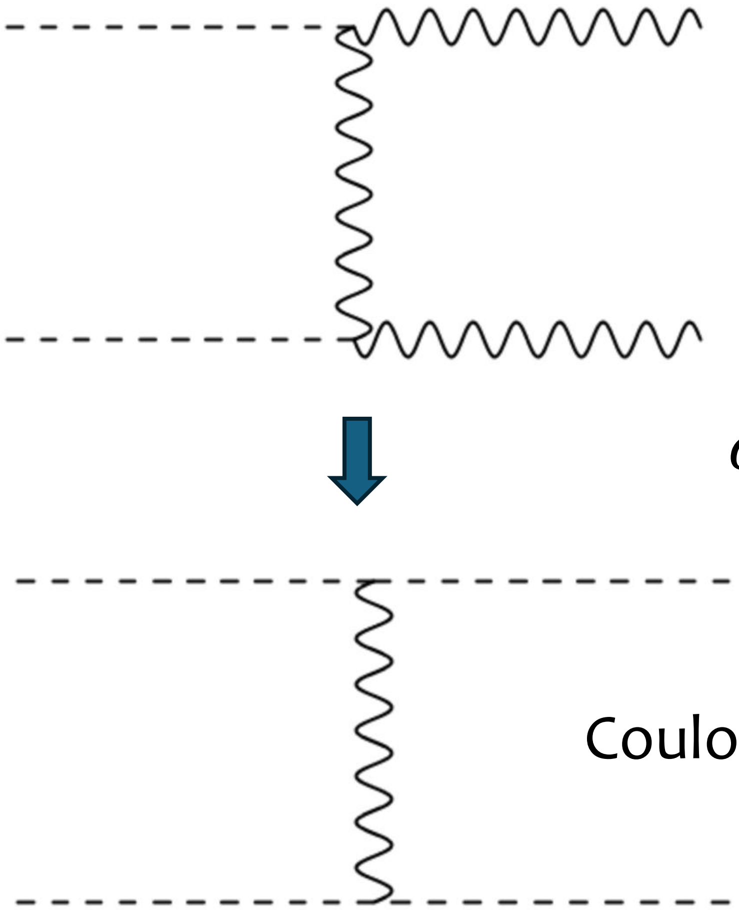
- Interactions that the cross section is not suppressed by large γ.

$$HH \to W^+W^-$$

$$HH \to W_L^+W_L^-$$

Goldstone equivalence theorem

$$HH \to \phi\phi$$



$$\sigma \sim \frac{g^4}{4\pi\, M_w^2}$$

Coulomb scattering

- W bosons will decay into quarks.
- Once most of the energy are in the form of quarks, thermalization will complete.
- It needs about $4\pi/g^4 \sim 100$ collisions to achieve thermalization.

Outline

- Motivations
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  - Strength Frequency   Spectrum
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- **GWs from Standard Model vacuum decay**
- Dark sector vacuum decay induced by Standard Model evolution
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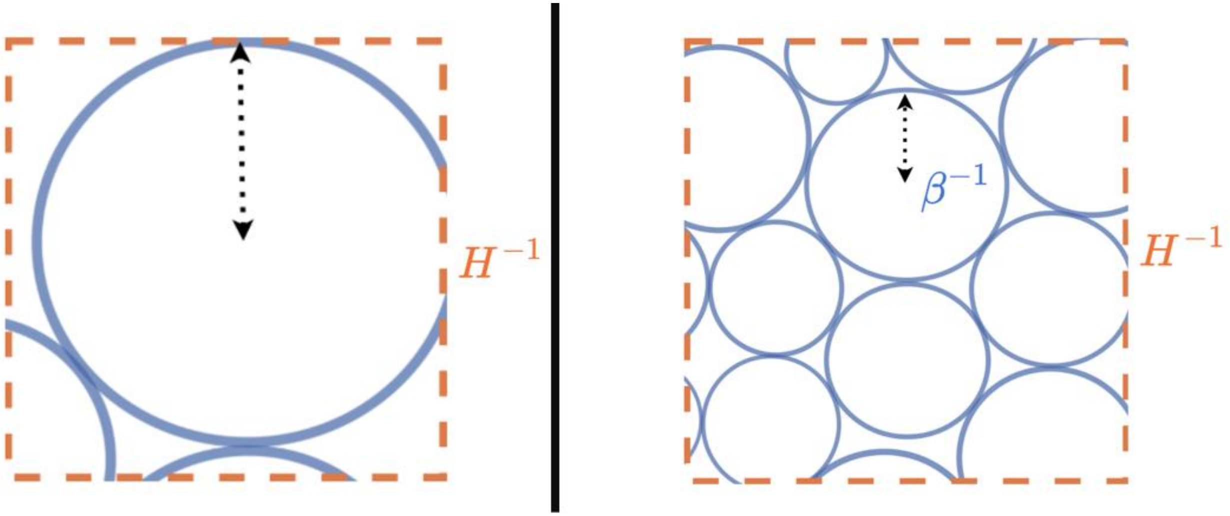
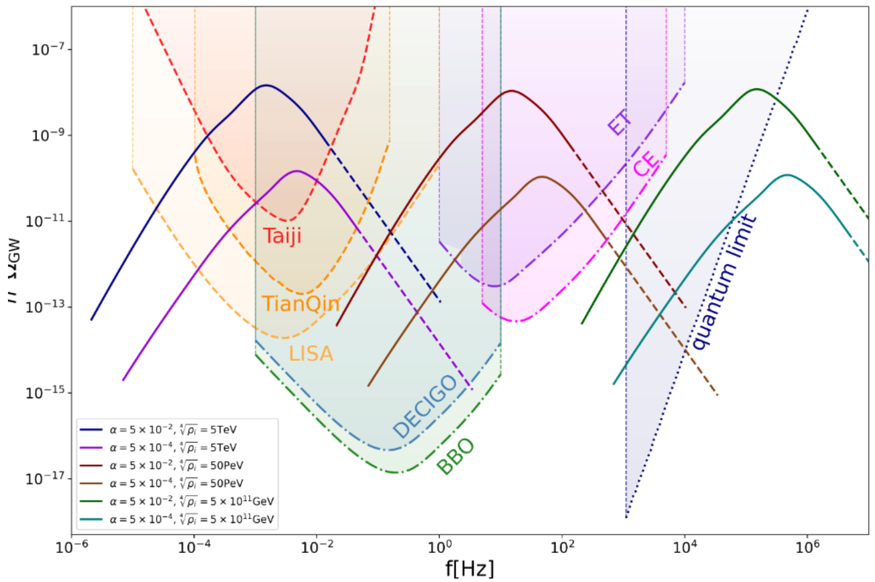
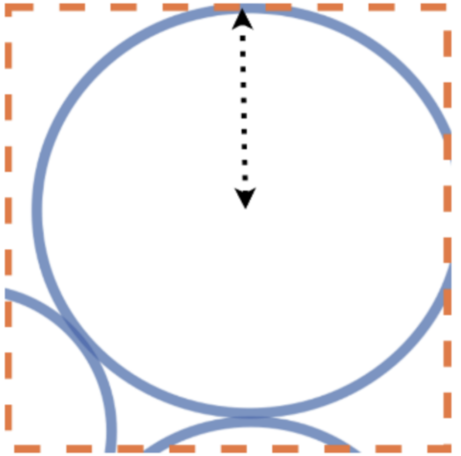




Dark sector triggered SM sector vacuum decay

- GW strength



$$\rho_{\rm GW} \sim \frac{GM^2}{R^4} \sim G\Delta\rho^2 R^2 \sim \frac{G\Delta\rho^2}{H^2}$$

$$\Delta\rho \sim \rho_R$$

$$\Omega_{GW} = \Omega_R \times \frac{\rho_{GW}}{\rho_R} \sim \Omega_R \times \frac{G\Delta\rho^2}{H^2\rho_R} \sim \Omega_R \times \frac{\Delta\rho^2}{\rho_{tot}\rho_R} \sim \Omega_R \times \frac{\Delta\rho}{\rho_{tot}}$$

$$\boxed{\Omega_{\rm GW} = C\Omega_R \times \frac{\Delta\rho}{\rho_{\rm tot}} \approx 3 \times 10^{-8} \times \frac{\alpha}{0.05}}$$

$C \approx 0.01$ (numerical simulation)

$\alpha = \dfrac{\Delta\rho}{\rho_{tot}} < 0.05$ Primordial black hole bound

HA and Tingyu Li, 2606.06587

GW spectrum

- $$\tilde{\mathrm{h}}_{+,\times}(\eta,\mathbf{k}) = 16\pi G \int_{-\infty}^{\infty} \mathrm{d}\eta'\, G\left(\eta,\eta',\mathbf{k}\right)\, a\left(\eta'\right)\, \tilde{T}_{+,\times}\left(\eta',\mathbf{k}\right)$$

$$G(\eta,\eta',\mathbf{k}) = \underbrace{y_1(\eta,\mathbf{k})y_2(\eta',\mathbf{k}) - y_2(\eta,\mathbf{k})y_1(\eta',\mathbf{k})}_{\text{Expansion of the Universe is important}}$$

lasts at least for several e-folds

- From the GW spectrum we can get the detailed information of the expansion of the universe.
- IR behavior $\rho_{\mathrm{SM}} \sim a^{-4}, \rho_{\mathrm{DS}} \sim a^{-6}$ (assuming kination)
- For $\Delta\rho$ close to the PBH bound, ρ_{SM} dominates the universe soon after the phase transition.

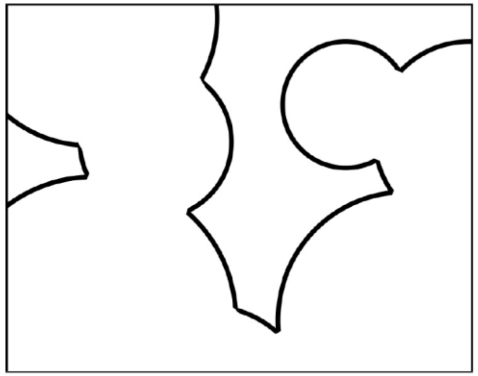
GW spectrum

$$\frac{\mathrm{d}\Omega_{GW}}{\mathrm{d}\ln k} \sim k^3 \left[\int \mathrm{d}t \sin(kt) \tilde{T}_{ij}^{\mathrm{TT}}(t,k) \right]^2$$

Minkowski background

$$\frac{\mathrm{d}\Omega_{GW}}{\mathrm{d}\ln k} \sim k^3 \left[\int a\, \mathrm{d}\eta' \sin(k\eta') \tilde{T}_{ij}^{\mathrm{TT}}(\eta',k) \right]^2$$

RD background

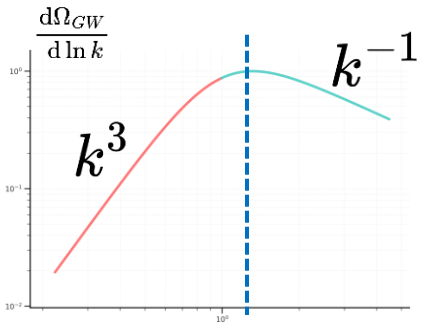


envelope model

For $k \to 0$

$$\frac{\mathrm{d}\Omega_{GW}}{\mathrm{d}\ln k} \propto k^3 \cdot [C]^2$$

Causality



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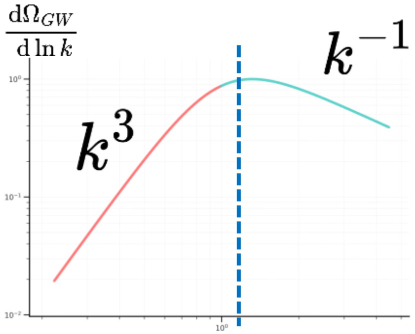
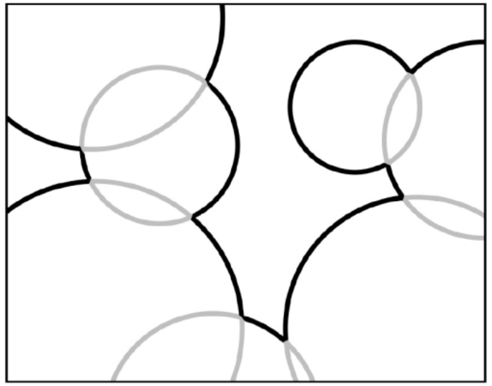


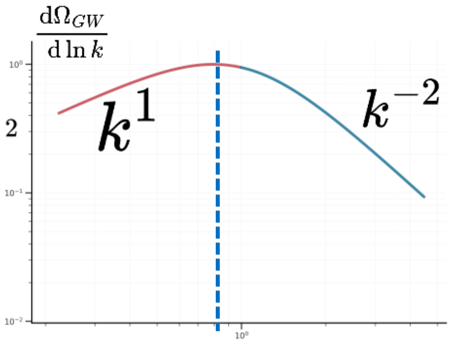


bulk flow model

For $k \to 0$

$$\frac{\mathrm{d}\Omega_{GW}}{\mathrm{d}\ln k} \propto k^3 \cdot [\frac{1}{k}]^2$$

$$\propto k^1$$



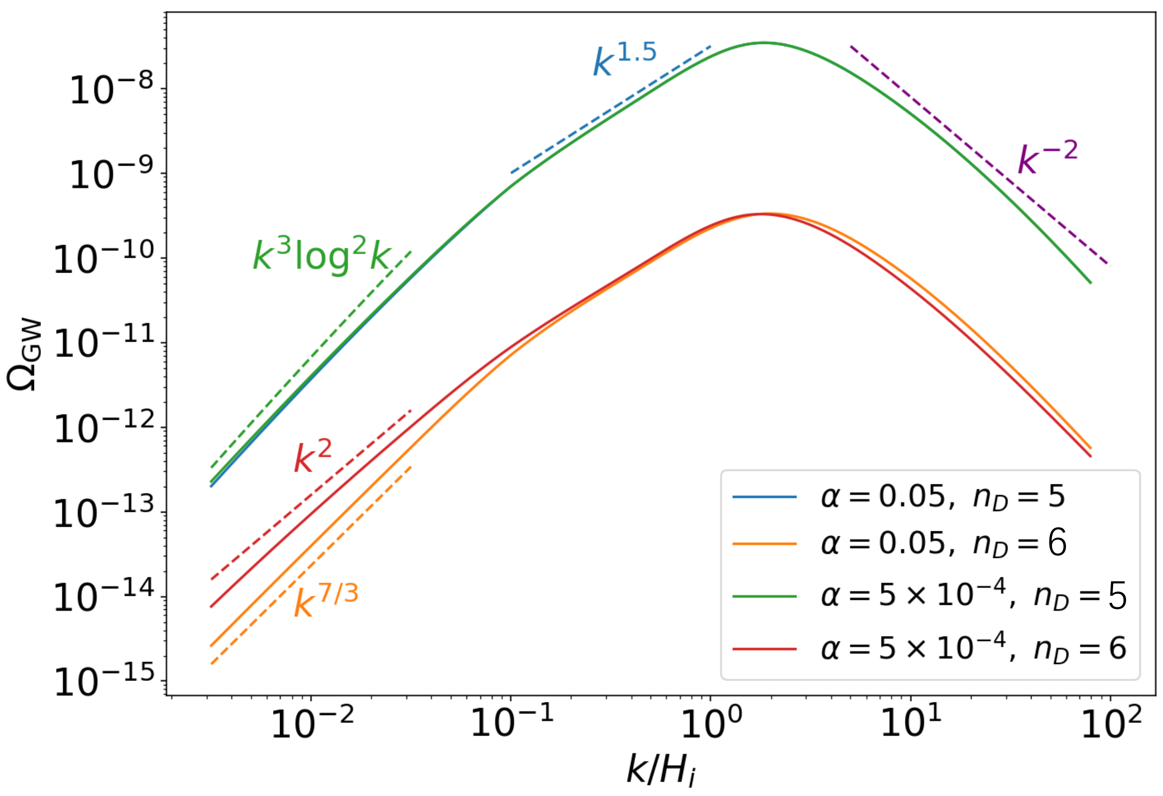
Our case:

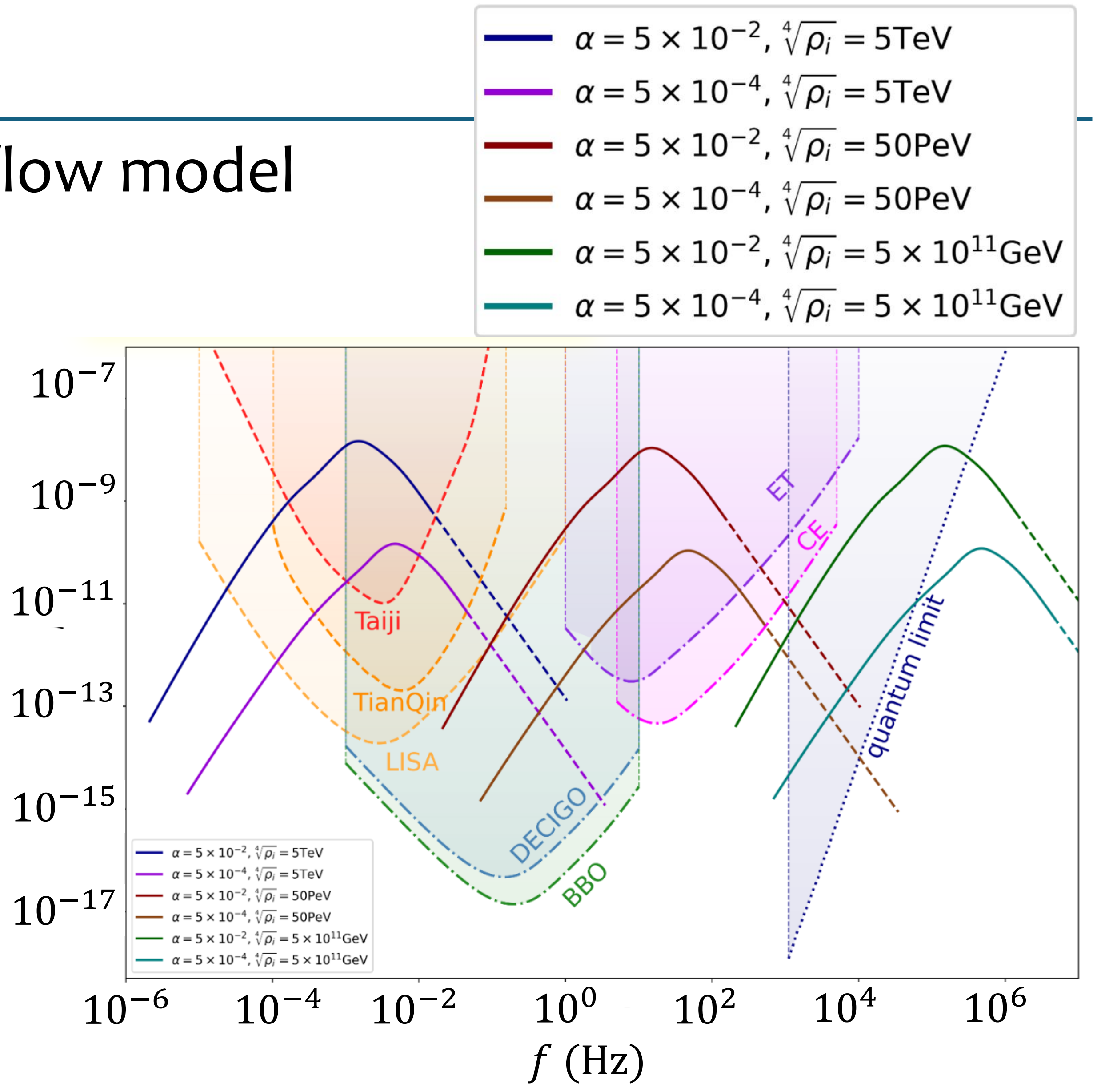
- Hubble friction
- RD Green's function
- long term source

$$\frac{\mathrm{d}\Omega_{GW}}{\mathrm{d}\ln k} \; ?$$

GW spectrum

- Numerical simulation using the bulk flow model





HA and Tingyu Li, 2606.06587

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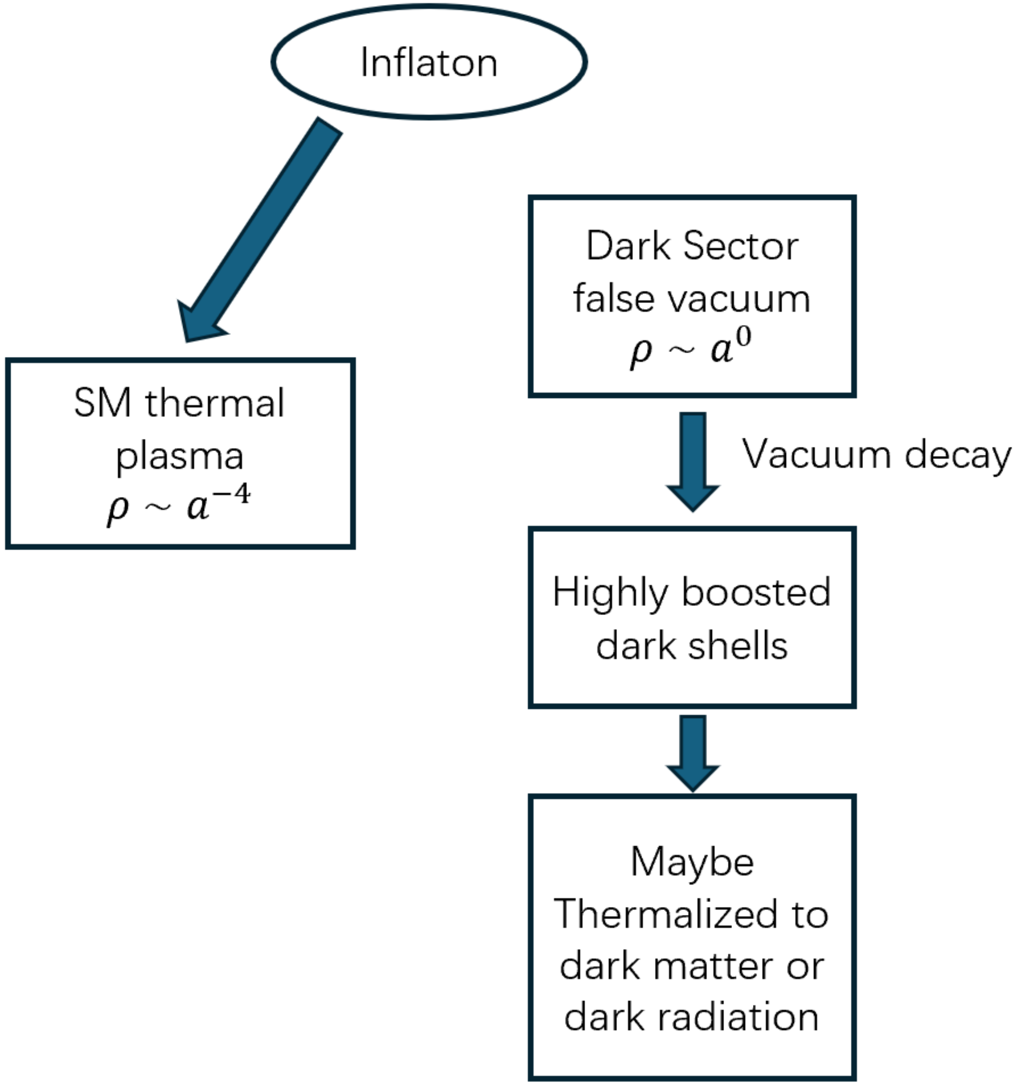


Properties of the GWs from DS vacuum decay

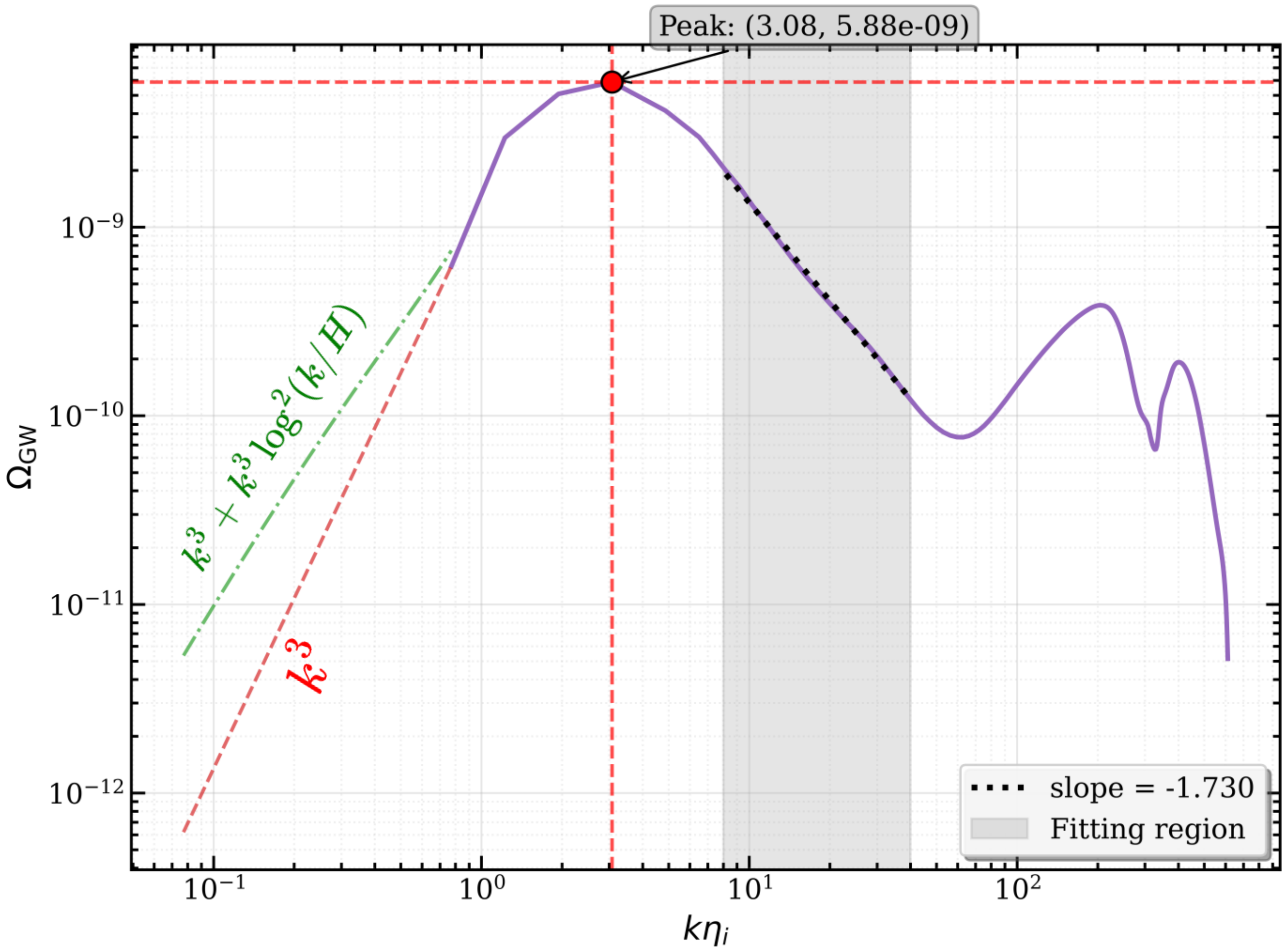
- Results:

- IR: $$\frac{d\rho_{\mathrm{GW}}^{\mathrm{IR}}}{d\ln k} \propto k^3 \log^2 \frac{k}{H_0} + O\left(k^3\right)$$

- UV: $$\Omega_{GW} \propto k^{-1.73}$$

- Peak: $$k_{peak}/H = 3.08$$

- $$\Omega_{\mathrm{GW}}^{\mathrm{peak}} = 1.5\Omega_R \left(\frac{L}{\rho}\right)^2$$



GW power spectrum from 2048^3 simulation

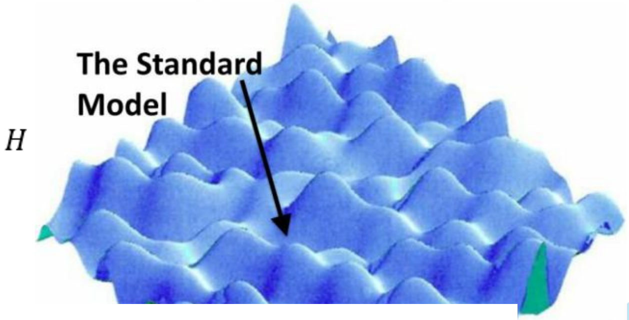
HA, Tingyu Li, Chen Yang, 2601.14366

Summary

Phase transitions in any sectors that
were in meta-stable state

H

The String Theory Landscape



SM

DS1

Gravity

...

DS3

DS2

Inflaton

SM false vacuum
$\rho \sim a^0$

Vacuum decay

Highly boosted
shells
$\rho \sim a^{-4}$

Redshift

Thermalized SM
plasma
$\rho \sim a^{-4}$

Dark Sector
$\rho \sim a^{-n}$

Maybe
Thermalized to
dark matter or
dark radiation

Inflaton

SM thermal
plasma
$\rho \sim a^{-4}$

Dark Sector
false vacuum
$\rho \sim a^0$

Vacuum decay

Highly boosted
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Maybe
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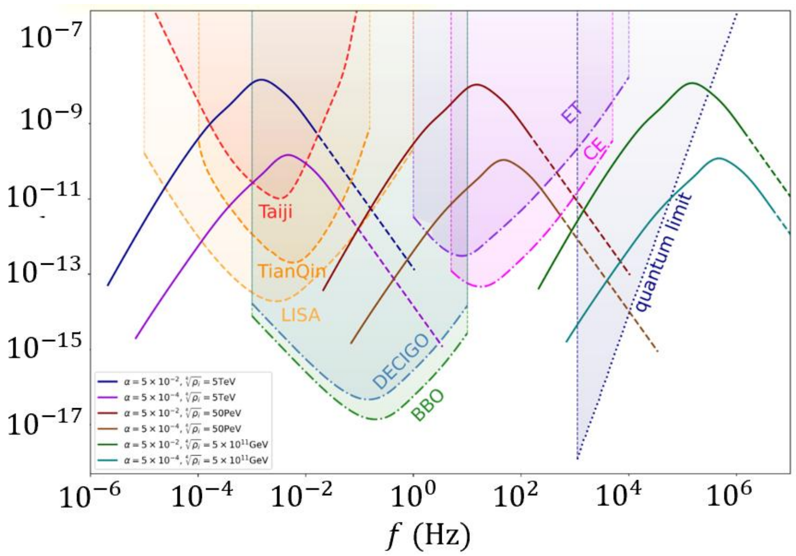


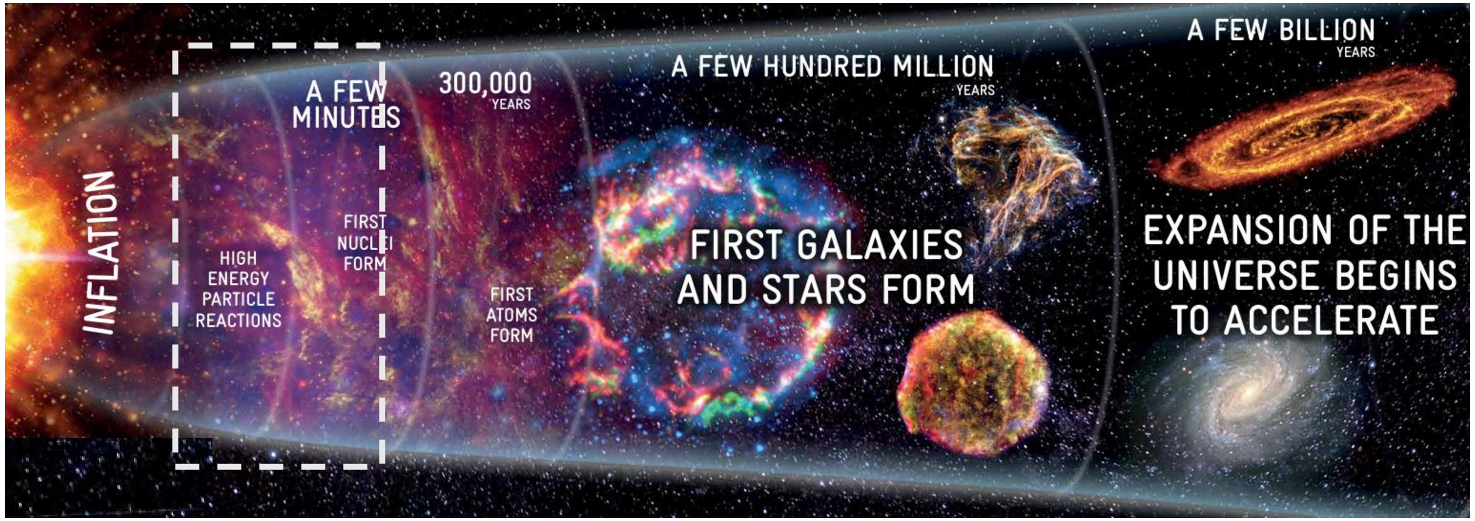
Backups

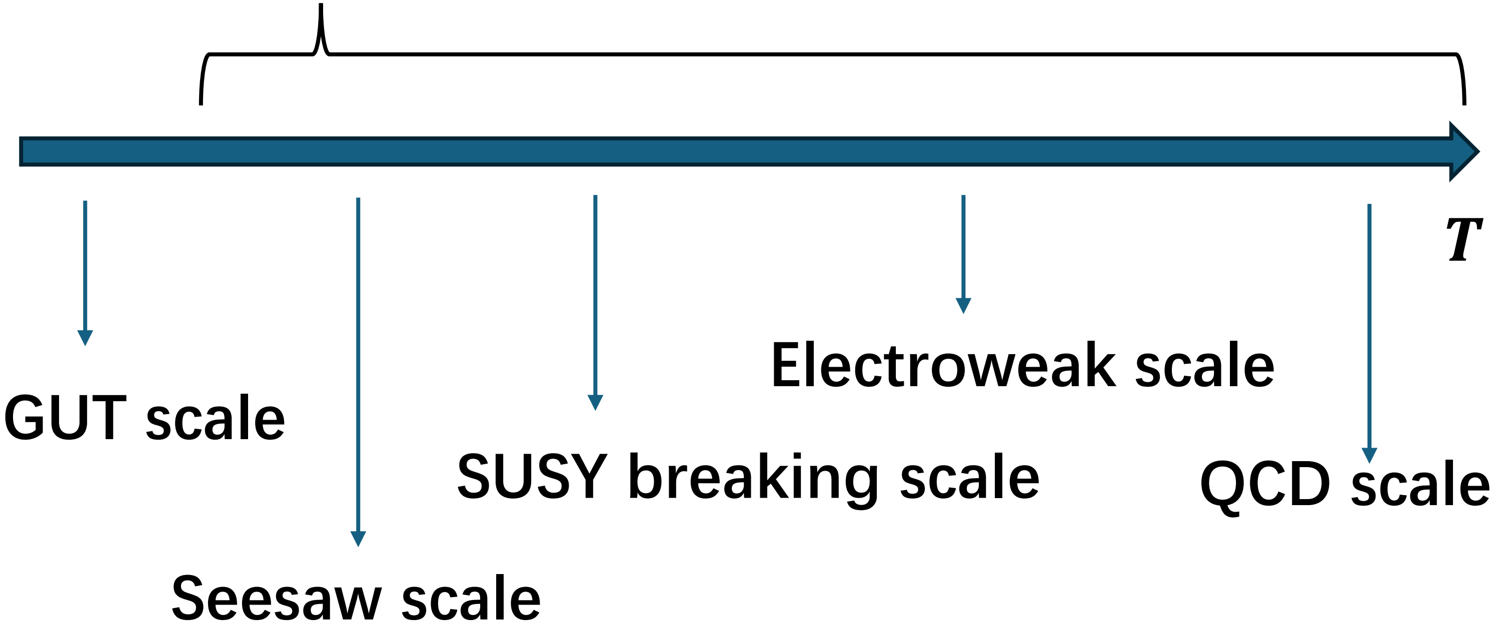
Motivations (Cosmological phase transitions)

- The temperature evolves.
- The Hubble expansion rate

  $\dot{a}/a = H \sim T^2/M_{pl}$

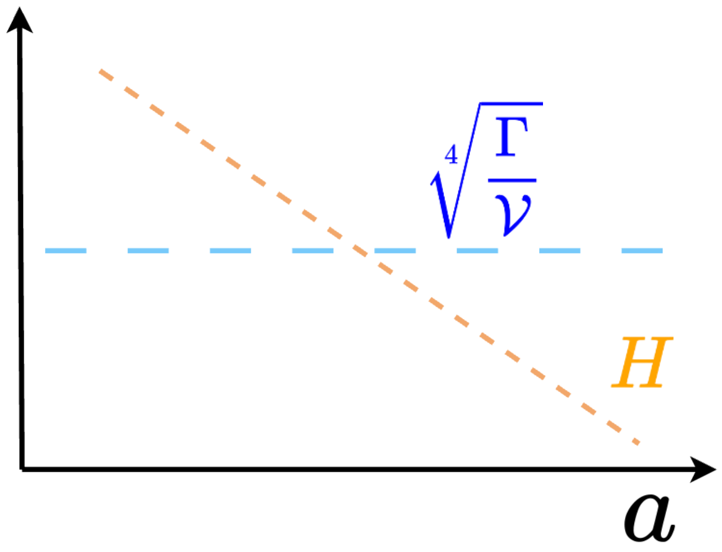
  is small!
- The evolution is mostly quasi-static.
- Phase transition happens when T goes across some typical energy scales.





Motivations

- No concept of β
- Bubble radius ~ H^{-1}



Vacuum decay PT:

$$\frac{\Gamma}{\mathcal{V}} = constant$$

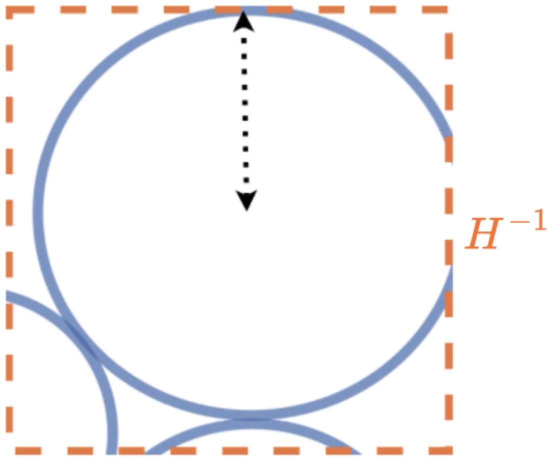
(No fluid, no plasma)

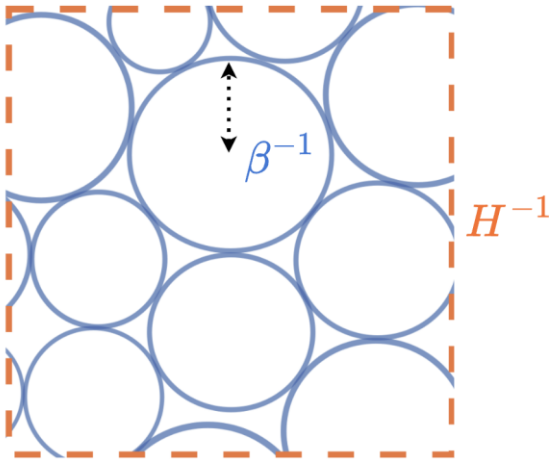
Thermal PT:

$$\frac{\Gamma}{\mathcal{V}} \sim \exp(\beta t)$$

Phase transition condition:

$$\frac{\Gamma}{\mathcal{V}} \sim H^4$$





Simplest realization of kination domination

- The inflaton field potential becomes flat right after the end of inflation.
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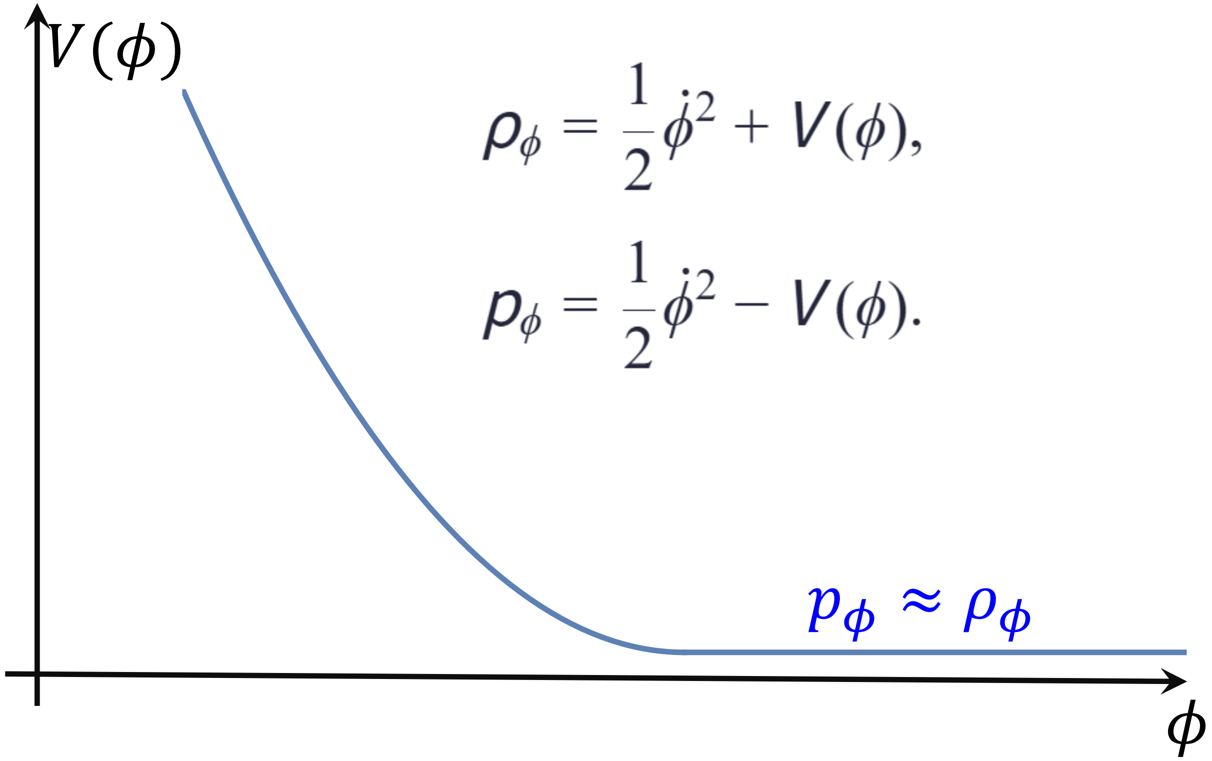
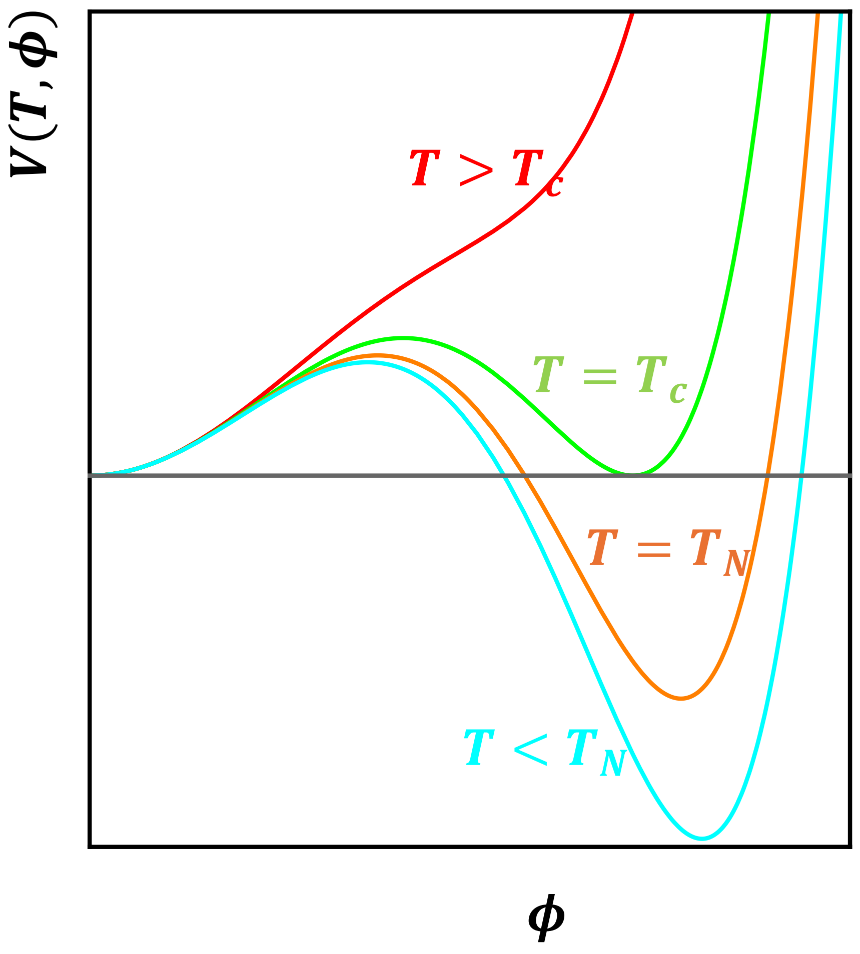
- $p_\phi \approx \rho_\phi$
- $n = 6$ (Friedmann equations)



GWs from a first-order phase transition

- Phase transition starts to complete when $\Gamma/V = H^4$ at $T = T_N$.

Coleman 1977, Callan and Coleman 1977, Linde 1981



$$m^4 e^{-S_3/T}$$

$m \sim T_N$

S_3: 3D bounce action

$$\frac{S_3}{T} = 4\ln\left(\frac{m}{H}\right)$$

$$\sim 4\ln\left(\frac{M_{pl}}{m}\right) \sim 150$$

for electroweak phase transitions

GW frequency

- $\beta = -\frac{d}{dt}\left(\frac{S_3}{T}\right) = -\frac{dT}{Tdt}\frac{d}{d\log T}\left(\frac{S_3}{T}\right) = H\frac{d}{d\log T}\left(\frac{S_3}{T}\right) \sim H\left(\frac{S_3}{T}\right) \sim 150H$ for EWPT

- $\lambda_{today} \sim \lambda_{phys}\left(\frac{T_N}{T_{CMB}}\right) \sim \frac{M_{pl}}{T_N^2} \times \left(\frac{S_3(T_N)}{T_N}\right)^{-1} \times \frac{T_N}{T_{CMB}} \sim \underbrace{10^7\ \mathrm{km} \times \left(\frac{1\ \mathrm{TeV}}{T_N}\right)}_{\text{LISA, TAIJI, TIANQIN}}$

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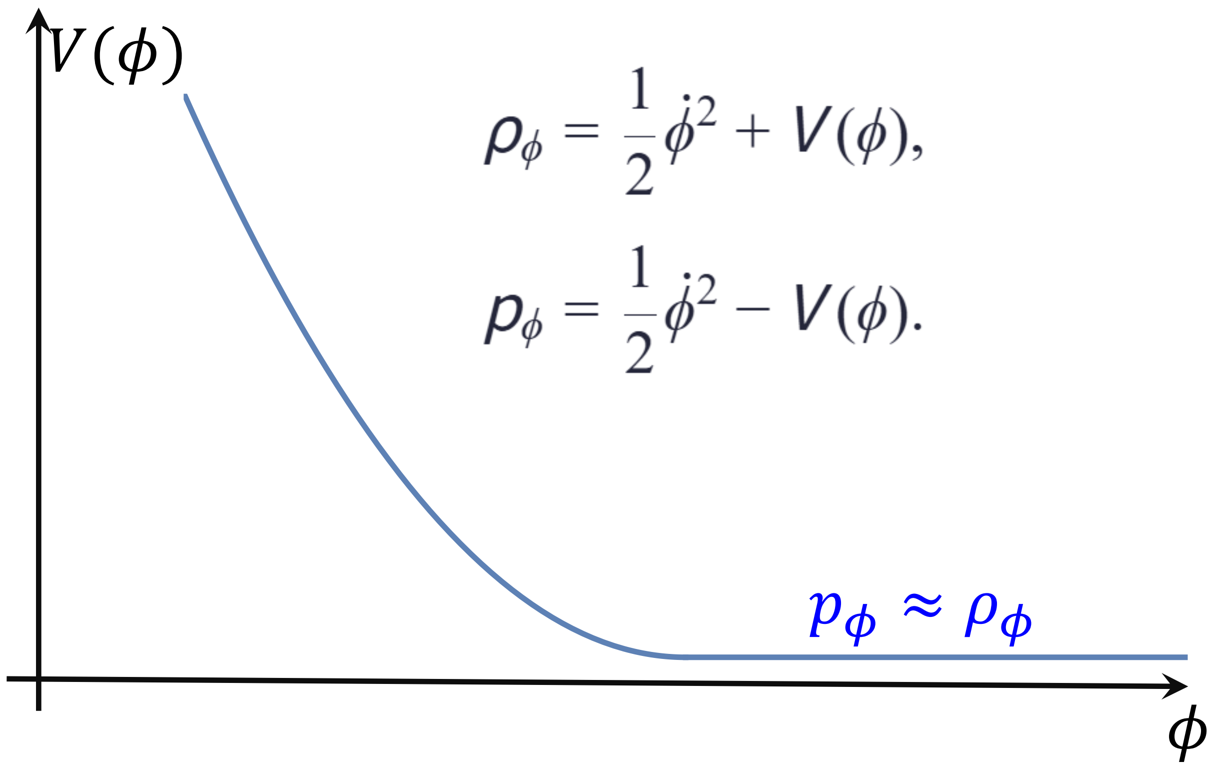

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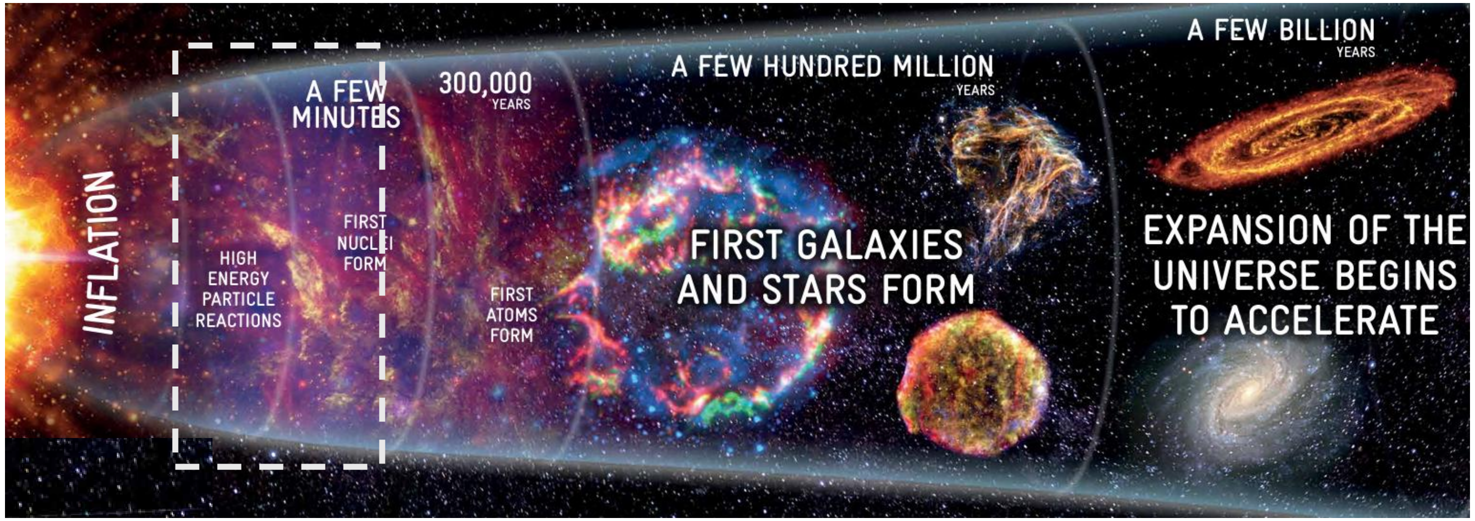

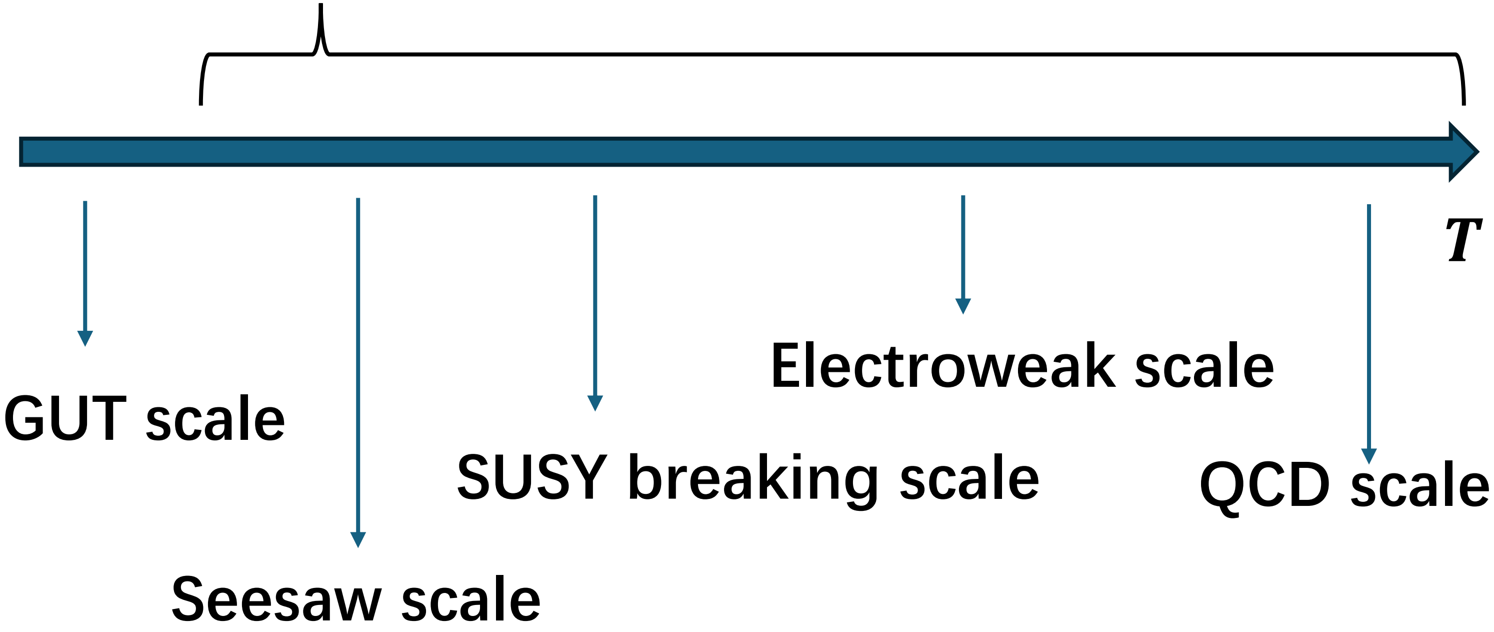

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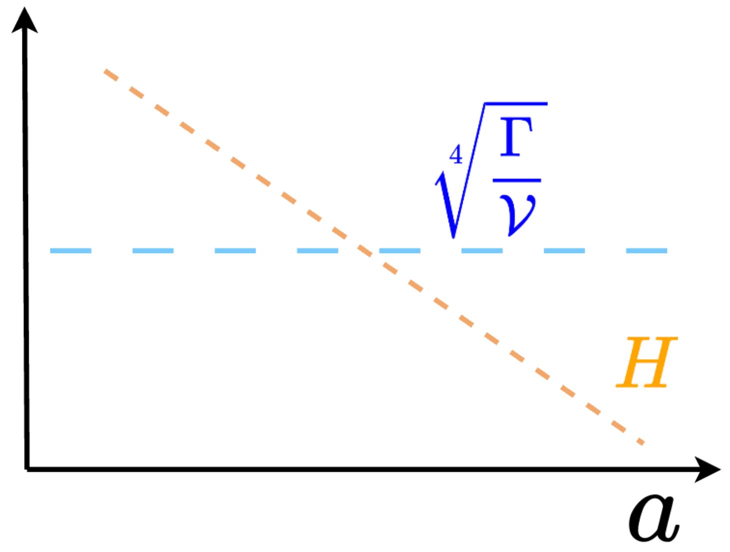

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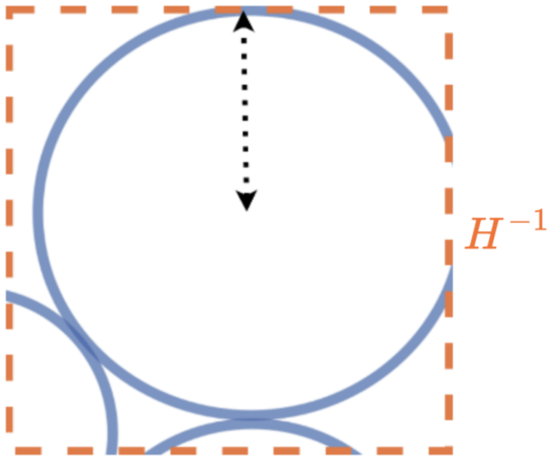

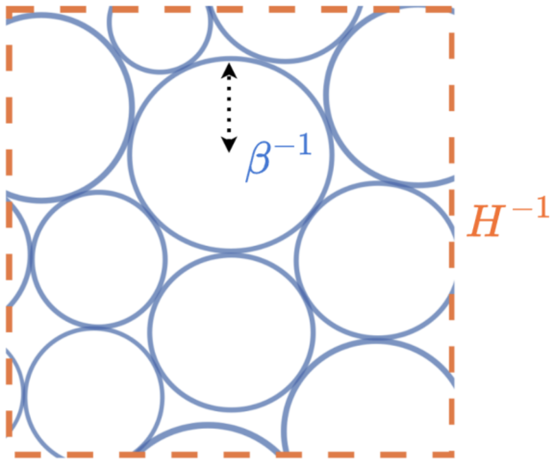

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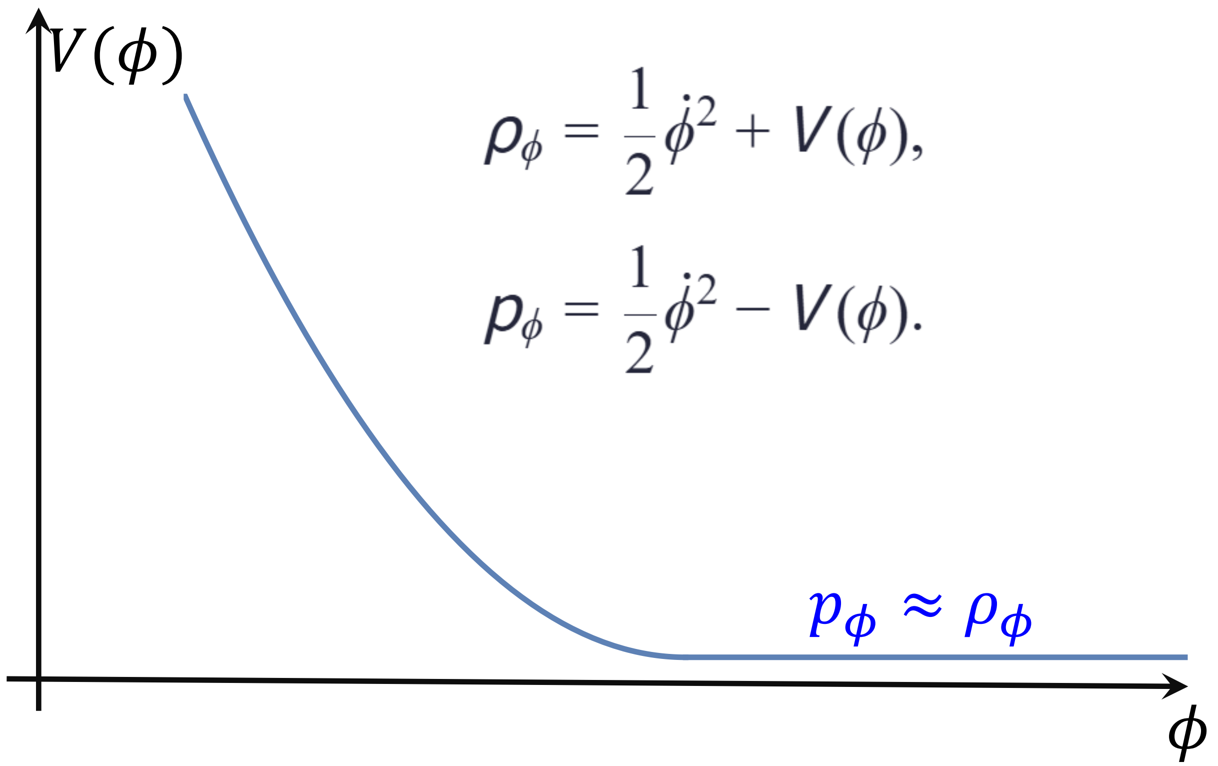

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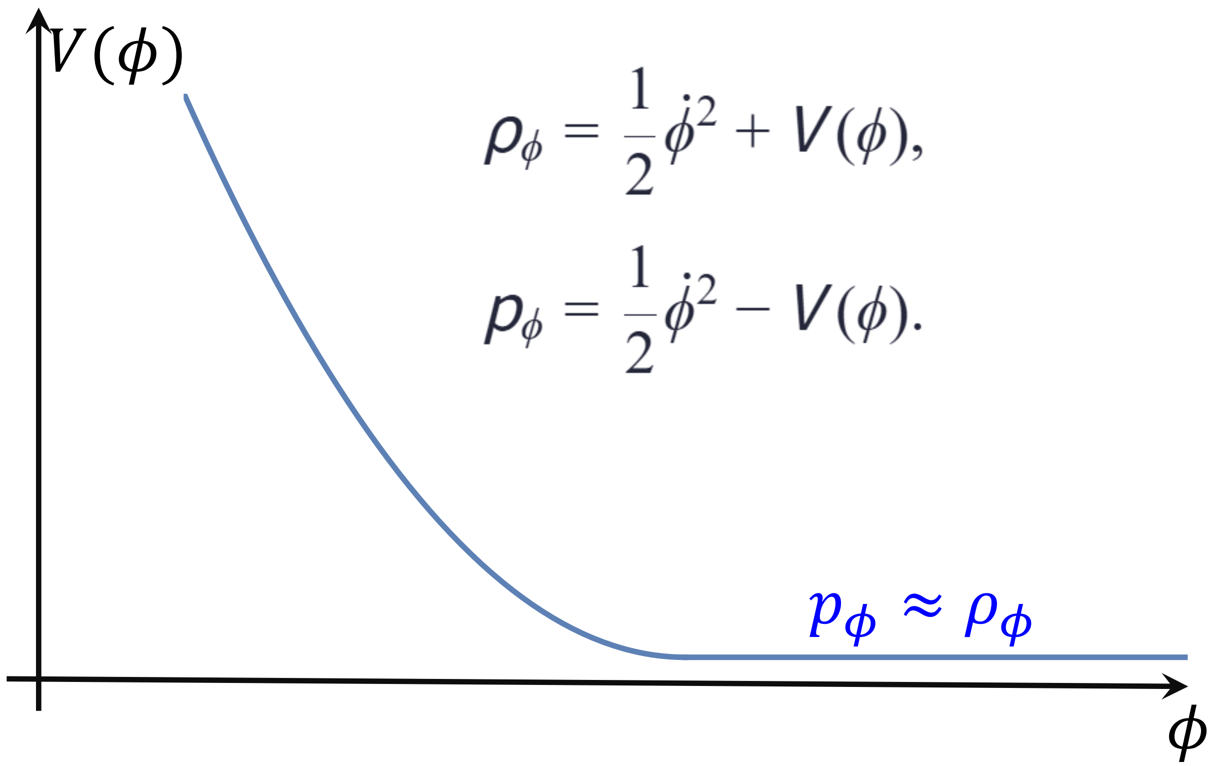


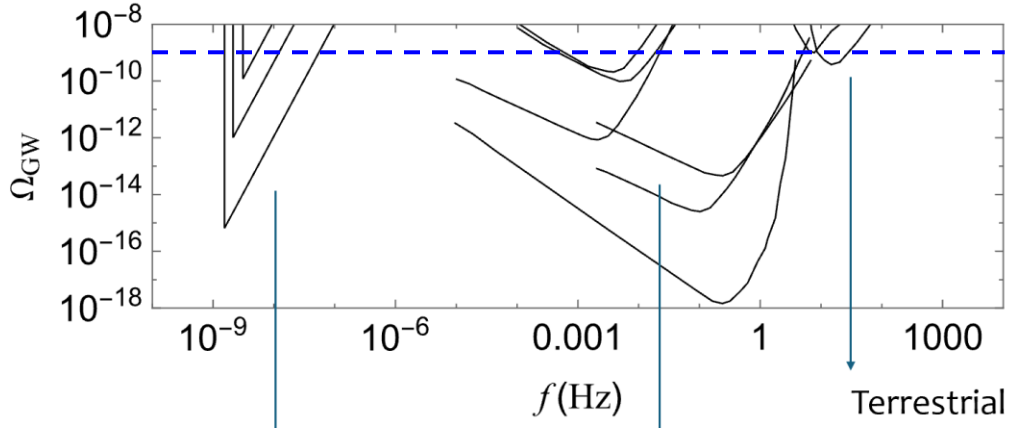
GW strength

- The metric around flat space-time $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- The gravitational waves are in h_{ij}^{TT}, the traceless and transverse part of h_{ij}.
- The gravitational potential are in h_{00}.
- In a relativistic system, we can use h_{00} to estimate h_{ij}^{TT}.

$$\rho_{\rm GW} \sim \frac{GM^2}{R^4} \sim \frac{G\Delta\rho^2}{\beta^2} \qquad H^2 \sim G\rho_R$$

$$\Omega_{\rm GW} = \Omega_R \times \frac{\rho_{\rm GW}}{\rho_R} \sim \Omega_R \times \frac{H^2}{\beta^2} \times \frac{\Delta\rho^2}{\rho_R^2} \approx \mathbf{10^{-9}}$$

$$\Omega_R \approx 10^{-5}, \frac{H}{\beta} \approx 0.01, \frac{\Delta\rho}{\rho} \approx 1$$



Pulsar timing arrays: IPTA, NanoGrav, CPTA …

Space GW detectors: LISA, TAIJI, TIANQIN, DECIGO, BBO …

Terrestrial detectors: Cosmic explorer, Einstein Telescope …